On the Optimisation of Operation and Maintenance Strategies for Offshore Wind Farms

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This work is dedicated to my parents for their support

Statement of Originality

I, Alexander Karyotakis confirm that the work presented in this thesis is my own. Where information has been obtained from other sources, I confirm that this has been indicated in the text. The contributions to knowledge I claim to have made in the subject area of mechanical engineering are as follows:

1. A comprehensive literature review in the area of offshore wind farm reliability, availability and maintenance issues has been conducted to understand the state-of-the-art and the limitations and technical challenges of current maintenance and repair practices.

2. The development and investigation of a planned intervention maintenance policy as a possible solution to the technical challenges identified in the current maintenance practices used by offshore wind farms.

3. The development of computer based models to simulate the maintenance processes of planned intervention maintenance policy, to investigate the benefits and drawbacks over current maintenance practices in terms of wind farm availability, cumulative energy output and cost of unit of energy produced.

4. The development of computer based models to investigate the CO_2 emissions associated with the maintenance expeditions to offshore wind farms when employing the current and the proposed maintenance strategies.

5. Investigate the deployment of a redundancy model for the converter system of offshore wind turbines as a possible solution to the identified technical challenge of reduced reliability levels of the offshore wind turbines.

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Abstract

This thesis reports on investigations undertaken into the reliability, availability and maintenance of offshore wind farms when considering different maintenance strategies, an understanding of which is fundamental when considering the technical and economical viability of existing and future offshore wind farms.

A comprehensive literature review has been undertaken in the areas of offshore wind farm maintenance strategies, offshore wind turbine reliability and accessibility issues, and CO2 emissions associated with maintenance expeditions for offshore wind farms. The limitations and disadvantages of current maintenance practices are identified and a planned intervention maintenance policy is proposed and examined in detail.

To help design a planned intervention maintenance policy, the offshore wind farm parameters that affect its technical and economical viability have been identified, which become the foundation for developing computer based models using Monte Carlo simulations to quantify the maintenance practices of the planned intervention maintenance policy. Different scenarios of the proposed solution are investigated to help quantify the technical and economical benefits over the current maintenance practises, in terms of wind farm availability, cumulative energy output, production cost of energy and CO2 emissions.

The research on the reliability of offshore wind turbines has shown that the power converter system is a critical item that suffers from high failure rates. This thesis reports upon the investigation of a hot standby redundancy on the wind turbine power converter system. A redundancy model is deployed to simulate the planned intervention maintenance policy for different offshore wind farm case studies in order to establish the effects of the hot standby redundancy on the offshore wind turbine operational performance.

The novel contribution of this work is claimed to be in the development of dedicated models for the reliability, availability and maintenance of offshore wind farms, which should lead in establishing a technical and economic benchmark for the parameters affecting offshore wind farms.

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I am also grateful to my second supervisor Bernard Eccles for his expertise and help to this research work, especially at the last stages of this thesis. His expertise in the field of reliability, availability and maintenance (RAM) engineering gave me the stimulation to direct this research to the correct pathway.

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Finally, I would like to thank my family for being there for me all these years, for their patience, support and encouragement.

Nomenclature

A	- Rotor disk swept area
A_{mean}	- Mean availability
a	- Axial induction factor
C_{DEC}	- Decommissioning cost
C_l	- Sectional lift coefficient
$C_{O\&M}$	- Annual operations and maintenance costs
C_p	- Rotor power coefficient
C_R	- Annual retrofit costs
C_s	- Annual social costs
C_{tot}	- Total expenditure
DV	- Driftuppfoljning av vindkaraftverk database
E_{tot}	- Total energy produced
$E[t^2]$	- Mean square availability
$f(t)$	- probability density function
$F(t)$	- Item unreliability
$h_{converter}$	- Failure rate of power converter
$h_p(t)$	- Failure rate function of primary redundancy item
$h_s(t)$	- Failure rate function of secondary redundancy item
$h_i(t)$	- Failure rate function of one of the parallel redundant items
$h_{system}(t)$	- Failure rate function of the parallel configuration system
I_{tic}	- Total investment costs
I_{total}	- Total investment costs including decommissioning costs
K_1	- Environmental stress factor
K_2	- Power rating stress factor
KE	- Kinetic energy
kV	- kilo volt
n_{elec}	- Electrical and Electronic item efficiency
n_{mech}	- Mechanical efficiency of wind turbine items
$n_{overall}$	- Overall efficiency of wind turbine
N_c	- Number of blades
PI	- Planned intervention maintenance strategy
P_{100}	- Power at 100% machine efficiency
P_{out}	- Total power output
P_{wind}	- Wind power
r	- Real interest rate
RR	- Reactive response maintenance strategy
R	- Rotor radius
$R_{converter}(t)$	- Reliability of the redundant converter system
$R_s(t)$	- Reliability function of a hot standby redundant system
R_i	- Reliability of a redundant item
t	- Time
T	- period
T_{EC}	- Economic lifetime of the project
U	- Wind speed
X	- Random numbers
α	- Annuity factor

λ_{tip}	- Tip speed ratio
λ_f	- Hazard or failure rate
μ	- Mean of distribution
ρ	- Density of the air
σ	- Standard deviation
ω	- Angular velocity
Ω	- Rotational speed of rotor

Abbreviations

AMP	- Asset Maintenance Plan
BWEA	- British Wind Energy Association
CAPEX	- Capital Expenditure
CA-OWEE	- Concerted Action on Offshore Wind Energy in Europe
CFRP	- Carbon Fibre Reinforced Plastics
CO2	- Carbon Dioxide
COD	- Concerted action for Offshore wind energy Deployment
DEWI	- Deutsches Windenergie – Institut
DFIG3G	- The doubly-fed induction generator with three stage gearbox
DFIG1G	- The doubly-fed induction generator with single stage gearbox
DDSG	- The direct drive synchronous generator with electrical excitation
PMG1G	- The permanent drive generator with single stage gearbox
DDPMG	- The direct drive permanent magnet generator
DOWEC	- Dutch Offshore Wind Energy Converter
HAWT	- Horizontal Axis Wind Turbine
HVDC	- High Voltage Direct Current
IEA	- International Energy Association
IGBT	- Insulated gate bipolar transistor
ISET	- Institut für Solare Energieversorgungstechnik
LCC	- Life – Cycle Costs
LPC	- Levelised Production Costs
LWK	- Landwirt-schafskammer Schleswig – Holstein database
MTTF	- Mean Time To Failure
$MTTF_s$	- Mean Time to Failure of a hot standby redundant system
MTTR	- Mean Time To Repair
MTPM	- Mean Time for Preventive Maintenance
NETA	- New Electricity Trading Arrangements
NFFO	- Non – Fossil Fuel Obligation
OECD	- Organisation for Economic Co-operation and Development
OPEX	- Operational Expenditure
OPTI-OWECS	- Structural and Economic Optimization of Bottom-Mounted Offshore Wind Energy Converters
OWECOP	- Offshore Wind Energy – Cost and Potential
O&M	- Operation and Maintenance
RECOFF	- Recommendations for Design of Offshore Wind Turbines
RCM	- Reliability centred maintenance
SADT	- Structure Analysis and Design Technique
ttf	- Time to failure
ttr	- Time to repair
tpm	- Time for preventive maintenance
VAWT	- Vertical Axis Wind Turbine
VSC	- Voltage source converter
WMEP	- Wissenschaftlichen Mess- und Evaluierungsprogramm database

Definitions

a) Reliability, Availability and Maintenance (RAM)

Reliability '*is the ability of an item to perform a required function under given conditions for a given time interval'*.[16] Reliability represents the probability of items to perform their required functions for a desired period of time without failure in specified environments, however reliability does not account for any repair actions that may take place.[1,2,3]

Maintainability '*is the probability that a given active maintenance action for an item under given conditions of use can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedures and resources'*.[16]

Accessibility '*is a qualitative or quantitative measure of the ease of gaining access to a component for the purposes of maintenance'*. [16]

Availability '*is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided*'. [16] In other words, availability represents the probability that a system is capable of conducting its required function when it is called upon, given that it is not failed or undergoing a repair action. Therefore, not only is availability a function of reliability, but it is also a function of maintainability.[5]

b) Capacity Factor

The windiness of a specific site where a wind farm is located, is measured by a parameter called capacity factor, which is defined as the wind turbines' actual energy output for time t, divided by the theoretical maximum energy output if the machine operated at its maximum rated power for time t.

c) Statistical Distributions

Skewness is the measure of the lack of symmetry of a statistical distribution. Distributions skewed to the right are positively skewed and distributions skewed to the left are negatively skewed, as shown in Figure def.1.[3,4]

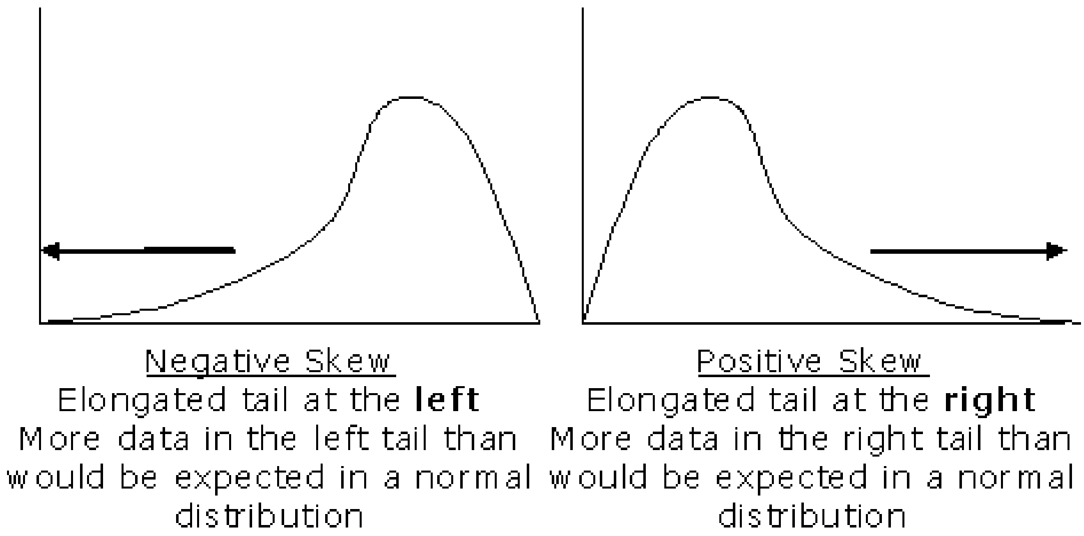

Figure def.1 Example of skewed histogram.[3,4]

Kurtosis is the measure of the extent to which probability is concentrated more around the mean and in the tails rather than in the mid-range relative to a normal distribution, which has a kurtosis of three.[3,4] If the kurtosis is higher than three then the distribution is called leptokurtic, with a sharper peak than the normal distribution, while for kurtosis lower than three, the distribution is called platykurtic and it is flatted as compared against the normal distribution, shown in Figure def.2.[3,4]

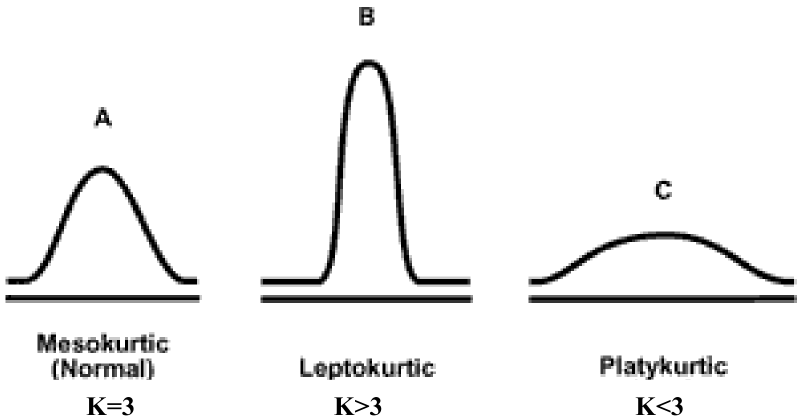

Figure def.2 Examples of kurtosis.[3,4]

d) Central Limit Theorem

The Central Limit Theorem states that '*if a large number of random samples of size μ are chosen from any populations, then the means of these samples will follow a normal distribution*'.[6] Regardless of the shape of the original distribution, even for very non-normal distributions, e.g. exponential, the distributions of averages of samples from the population approach the shape of a normal distribution. When considering the above definition of the Central Limit Theorem, as the number of samples increases, then skewness and kurtosis of the distribution should approach zero and three respectively, thereby representing a normal distribution.[6]

e) Definitions of PM 1 and PM 2

PM 1 and PM 2 are subsections of the planned intervention maintenance policy for offshore wind farm that is being investigated in this thesis.

- PM 1 is defined as a planned intervention maintenance policy with one scheduled visit per operational year to the offshore wind farm for maintenance tasks. This period is typically during July, and this is defined by weather and other constraints for accessibility issues which are discussed further in Chapters 3 and 4.

- Likewise, PM 2 is defined as a planned intervention maintenance policy with two scheduled visits per operational year to the offshore wind farm for maintenance tasks. These periods are typically during May and October.

PM 1 and PM 2 are alternative planned intervention maintenance policies and they cover a combination of the following tasks, during the visit to each offshore wind turbine:

- Diagnostic measurement (e.g. vibration analysis)
- Inspection
- Preventative maintenance (cleaning, oil and consumable spare replacement, adjustment, tightening bolts etc)
- Repairs

The combination of the above tasks is planned in advance, based on best information available, and also is modified to accommodate findings from diagnostics and inspections undertaken at the time.

In addition repair can be any one of the following:

- Repair in situ (not very common)
- Exchange and repair remotely (usually on shore)
- Exchange and overhaul remotely (usually on shore)

Appendix B.6 (p. 364) gives a list of the most common failures of the major wind turbine items and also maintenance tasks that are carried out during a visit to offshore wind turbines.

1 Introduction

1.1 Background and Motivation

Offshore wind farm development has a short history of less than 30 years with the first offshore wind farm being built off the coast of Denmark in 1991.[7] Today, there are 29 operational offshore wind farms with another four in their last stages of installation (see Table 1.1) with the majority of these consisting of only a modest number of wind turbines. For the future, greater numbers of larger offshore wind farms having more powerful wind turbines are being planned, including 10 GW for the UK as part of its energy development strategy.[8,8]

The current offshore wind turbines were not designed to cope with the harsh conditions of the marine environment, as onshore wind turbines have been used.[7,8,10,11] The introduction of the marine environment has resulted in the reduction of reliability levels for the offshore wind turbines, as explained in the critical review presented in Chapter 2.

The current practises used by the offshore wind farm operators for maintenance is reactive response, i.e. to undertake repairs of wind turbines at the first opportunity, in other words, as soon as a failure has been detected an expedition is initialised for repairs.[10,12,13] This Operation and Maintenance (O&M) strategy has been reported to be based on over-maintenance practices, as discussed in the critical review in Chapter 2, leading inevitably to high cost per unit of energy produced. Although this current strategy has not yet been proven to be the optimum economic solution, it is the only practical one taking into consideration the relative low number of wind turbines currently in operation, in existing offshore wind farms, which are located close to shore at shallow waters. However when considering future offshore wind farms, which are likely to be located far offshore, in remote locations, with increased power rating over today's machines, then such a maintenance strategy is likely to be expensive, require large resources and be technically challenging.

This thesis is therefore concerned with proposing and examining a possible solution in the technical challenge of maintenance of remote large offshore wind farms. Computer models of a planned intervention maintenance strategy for offshore wind farms have been developed and simulated to investigate its technical and financial benefits when compared against current practice. Considering a planned intervention maintenance policy, the repairs and maintenance of offshore wind turbines are undertaken at predefined intervals during the operational year. Monte Carlo simulations and computer based models have been used to simulate the planned intervention maintenance policy with different parameters, e.g. wind farm capacity factors, time to failure, time to repair, transportation means and distance to shore, to establish technical and economic feasibility.

Table 1.1 The existing and near future offshore wind farms in Europe listed by the year of installation [7,14,15] (Near future projects are indicated in green).

Location	Country	Capacity in MW	No of Turbines	Turbine manufacturer	Year of Installation
Vindeby	Denmark	5	11	Bonus	1991
Lely	Holland	2	4	NedWind	1994
Tuno Knob	Denmark	5	10	Vestas	1995
Irene Vorrin	Holland	17	28	Nordtank	1996
Bockstigen	Sweden	3	5	WindWoeld	1998
Blyth	UK	4	2	Vestas	2000
Middelgruden	Denmark	40	20	Bonus	2000
Utgrunden	Sweden	10	7	GE-Wind	2000
Yttre Strengung	Sweden	10	5	NEG Micon	2001
Horns Rev	Denmark	160	80	Vestas	2002
Arklow Bank	Ireland	25	7	GEWE	2003
North Hoyle	UK	60	30	Vestas	2003
Nysted	Denmark	158.4	72	Bonus	2003
Samso	Denmark	23	10	Bonus	2003
Scroby Sands	UK	60	30	Vestas	2004
Frederikshavan	Denmark	7.6	3	Various	2004
Kentish flats	UK	90	30	Vestas	2005
Ronland	Denmark	17.2	8	Bonus, Vestas	2006
Barrow	UK	90	30	Vestas	2006
Breitling	Germany	2.5	1	Nordex	2006
EMS-Enden	Germany	4.5	1	Enercon	2006
Beatrice	UK	10	2	RePower	2007
Egmond ann Ze	Holland	108	36	Vestas	2007
Burbo Bank	UK	90	25	Siemens	2007
Q7-PA	Holland	120	60	Vestas	2008
Thornton	Belgium	30	6	Repower	2008
Robin Rigg	UK	180	60	Vestas	2008
Lynn Dowsing	UK	194.4	54	Vestas	2009
Horns Rev 2	Denmark	209	91	Siemens	2010
Gunfleet Sands	UK	172.8	48	Siemens	2010 (plan)
Rhyl Flats	UK	90	25	Siemens	2010 (plan)
Thanet	UK	300	100	Vestas	2010 (plan)
Alpha Ventus	UK	630	175	Siemens	2012 (plan)

As the wind farms move further offshore, the question of how 'green' offshore wind farms are, is raised. The maintenance of each wind turbine necessitates the use of ships and helicopters which emit CO2 and other emissions, and when compared against onshore equivalent wind farms these have the potential to be significant. In this thesis computer based models are developed to calculate the likely amount of CO2 emissions attributed to repairs and maintenance expeditions to offshore wind farms and a comparison undertaken between the results obtained from the corrective maintenance strategy and the planned intervention maintenance policy.

Investigations examining the O&M strategy of offshore wind farms revealed that offshore wind turbines suffer from high failure rates. Further investigations identified that the offshore wind turbine critical items in terms of reliability levels were the electrical systems. A redundancy model is investigated as a possible solution to this technical challenge for the wind turbine converter system in order to simulate how the offshore wind farm availability, cumulative energy output, CO2 emissions and production cost of energy are affected.

1.2 Aims and Research Objectives

The aims and objectives of this research are:

To understand Reliability, Availability and Maintenance strategies of offshore wind farms by critically reviewing the literature. This necessitates gaining knowledge on O&M strategies of offshore wind farms and identifying the limitations and technical challenges.

To propose possible solutions to the technical challenges identified for maintenance practices of offshore wind farms. A planned intervention maintenance policy to be modelled and simulated to investigate possible technical and economic benefits, when compared against current maintenance practices.

To develop a reliability model of the offshore wind turbines to investigate how the marine environment affects their failure rates and calculate accurate ranges for offshore wind turbines based on reported hard data for onshore wind turbines through the use of item empirical stress factors. This investigation to be performed uses the assessment to be conducted in a number of different wind turbine reliability databases for three European counties.

To develop computer aided models based on Monte Carlo simulations to investigate the maintenance operations of offshore wind farms and simulate the proposed solution of planned intervention maintenance policy. The computer aided models will allow the comparison of the planned intervention maintenance policy against the current O&M practices in terms of wind farm availability, energy output, cost of unit of energy produced and CO2 emissions.

To investigate how 'Green' the offshore wind farms are. The UK is currently confronted by EU regulations to minimise the CO2 emissions from electricity generation. In that respect renewable energy projects have been deployed and are feeding the national grid of many European countries with increasing rate of development every year. However maintenance of an offshore wind farm involves generation of CO2 emissions from the support vessels and helicopters. **Computer based models are to be developed** to investigate how green the offshore wind farms are, in terms of CO2 emissions by comparing the results for the current maintenance practices with a planned intervention maintenance policy.

To investigate the technical challenge of the reduced reliability levels of offshore wind turbines through the assessment of the redundancy model for the power converter system of the offshore wind turbines.

1.3 Outline of Thesis

This thesis is divided into 8 chapters:

Chapter 1. This chapter gives a background introduction to the research carried in this thesis. The research objectives and author's publications are presented.

Chapter 2. In this chapter a comprehensive literature review of the reliability, availability and maintenance issues of offshore wind turbines is undertaken to identify the technical challenges in the current maintenance practices.

Chapter 3. In this chapter possible solutions are proposed for the identified technical challenges of O&M of offshore wind farms and the technical advantages and disadvantages between the current maintenance practices and the proposed solution of planned intervention maintenance policy are identified.

Chapter 4. This chapter presents the development of computer based algorithms for the O&M model for the proposed solution of the planned intervention maintenance policy.

Chapter 5. This chapter presents the validation and verification of the developed models for the planned intervention maintenance policy in order to provide added confidence for the outputs.

Chapter 6. This chapter presents and explains the output results obtained from the simulation of planned intervention maintenance policy O&M model for different offshore wind farm case studies and the comparison against the current practices. This chapter also examines the CO_2 emissions of offshore wind farms through the development of computer aided programs for the current maintenance practices of offshore wind farms which are compared against the results obtained for the planned intervention maintenance policy.

Chapter 7. In this chapter the redundancy model on the offshore wind turbine converter system is investigated and simulated for different offshore wind farm case studies in order to examine how the model affects the outputs of the developed O&M model.

Chapter 8. General conclusions of the research work carried out in this thesis are discussed with suggestions for outlines of future research work.

1.4 Publications

The following publications were generated during the course of the research work.

1. Karyotakis A. **Offshore Renewable Energy.** Shipping International Monthly Review, October 2004.

2. Karyotakis A. **Renewable Energy Conference in Athens**. Shipping International Monthly Review, April 2005.

3. Karyotakis A. **Marine and Offshore Power engineering latest trends**. Shipping International Monthly Review, April 2006.

4. Karyotakis A. and R.W.G. Bucknall. **Planned intervention as a maintenance and repair strategy for offshore wind turbines**. Journal of Marine Engineering and Technology. Part A, Volume 2010, Number 16, pp 27-35. January 2010.

The research work in this thesis was presented at the **Wind Energy Operations and Maintenance Summit**, organised by '**Wind Energy Update'** in November 2008 in London UK. The author of this thesis was invited by '**Wind Energy Update'** to participate and contribute with the research work presented in this thesis at the production of the second edition of '**Wind Energy Operations and Maintenance Report**' focused on offshore wind farms. The work will be carried out in 2010-11.

2 Literature Review

2.1 Introduction

The UK is planning to develop a significant offshore wind turbine generation capacity to contribute towards the reduction of greenhouse gas emissions from the electricity generation sector. The maintenance of high numbers of offshore wind turbines represents a major challenge to ensure a reliable yet cost effective source of electricity, as compared to onshore wind farms, which are more accessible. A comprehensive review is needed to identify the technical challenges in the current practices of maintenance strategy for offshore wind farms and the parameters affecting the maintenance expeditions and their costs. A planned intervention maintenance policy is proposed and explained in this chapter as a possible operation and maintenance (O&M) strategy for large offshore wind farms, since the current practices are reported to be effective but expensive. Finally, an investigation into the CO2 emissions from offshore wind farms was undertaken to quantify the contribution of offshore renewable projects to greenhouse gases.

2.2 Review of maintenance strategies

Every system in operation over a defined period can experience some kind of malfunction or failure at some point in its life-cycle.[1] The process of repairing or refining equipment upon failure, and of routinely refurbishing and renewing components/parts to prevent failure or bringing the failed system to an operating state, is defined as maintenance.[1] The definition of maintenance is given below by British Standards;[16] '*The combination of all technical and associated administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform its required function'*.

There are two main maintenance strategies that are generally used; the proactive maintenance and the corrective maintenance. The primary difference between corrective and proactive maintenance is that a problem in the system must exist before corrective maintenance actions are taken, whilst proactive maintenance tasks are intended to prevent occurrence of a problem in the first place.[17]

The proactive maintenance is described as '*the maintenance carried out at predetermined intervals or depending on prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item'*.[16] In simple words, the proactive maintenance operation is initiated prior to a failure or malfunction in the system in order to prevent such occurrence. This strategy includes '*the care and servicing by personnel for the purpose of maintaining equipment and facilities in satisfactory operating condition by providing for systematic inspection, detection and correction of incipient failures either before they occur or before they develop into major defects*'.[1,2]

<u>Proactive maintenance</u> is a strategy whereby breakdowns are avoided or postponed through activities that monitor equipment deterioration and initiate minor repairs to restore items or systems to full working order. This maintenance activity can be divided

into preventive and predictive maintenance, with both aiming to reduce the probability of unexpected system failures.

Preventive maintenance, often referred to as planned/scheduled maintenance, comprises of maintenance activities that are undertaken after a specified period of time or percentage of system utilisation.[18,19] The preventive maintenance is based on statistical reliability analysis of the system, i.e. the estimated probability that the equipment will fail in a specified period of time. Typical maintenance tasks undertaken include equipment inspection, lubrication, parts replacement, cleaning and adjustments.[18,19] The reduced probability of system breakdowns and extension of system life are the main advantages of preventive maintenance, whilst the need to interrupt production at scheduled intervals to perform maintenance tasks is the main disadvantage.

Predictive maintenance, often referred to as condition-based maintenance, is when maintenance tasks are initiated in response to a specific system condition,[20,18] which is diagnosed by equipment (indicators) used to measure the physical condition of the system, e.g. temperature, vibration, noise, lubrication and corrosion.[21] When one of these indicators reaches a specified level, which indicate system deterioration, maintenance work is undertaken to restore the system to its initial condition. Predictive maintenance is based on the same principle as preventive maintenance to reduce the probability of system breakdown, although it employs different criteria for determining the need for specific maintenance activities, which are performed only when the need is imminent and not a specified period of time.[19,22]

Corrective maintenance is described as '*the maintenance carried out after fault recognition or degradation and is intended to put an item into a state in which it can perform a required function*'.[16] This strategy also associates part replacements but not systematic inspection by monitoring of the system as in predictive maintenance. In other words, as soon as a item has failed the maintenance operation is initialised, i.e. the system is allowed to run until failure, and then the failed equipment is repaired or replaced.[16] When considering corrective maintenance tasks, temporary repairs may be made in order to return the system to operation, with permanent repairs delayed until a later time. Corrective maintenance could be applied to computer software and software engineering applications, where flaws in the computer code are repaired only after system malfunction.

2.2.1 Optimisation of maintenance practices

Maintenance tasks in conventional power plants, e.g. coal fired and steam turbine power plants, are performed during low-load seasons, i.e. when the demand for electricity is low, and the maintenance time depends on system risk (critical items) and production cost.[23] Effective maintenance strategies for power plants aim to reduce the frequency of service interruptions and the undesirable consequences of such interruptions, e.g. loss of energy production. The maintenance strategy affects item and system reliability in a way that if too little maintenance is performed, i.e. the system is returned in an 'as good as operating' condition, then this may result in an excessive number of costly failures and poor system performance, which in turn results in the system reliability being degraded.[23,24,3] However, if maintenance tasks are performed too often, reliability may improve but the cost of maintenance may potentially increase.[3,24] Therefore a cost-effective maintenance strategy optimisation involves balancing the cost of maintenance tasks and system reliability.[23]

The main purpose of maintenance optimisation for power plants is to determine the most cost-effective maintenance strategy, which will provide the best possible balance between direct maintenance costs, e.g. labour, resources, materials and administration costs, and the consequences or penalty of not performing maintenance as required, e.g. loss of production and anticipated income and profit.[16,25] When considering the maintenance strategies then three categories can be used known as the reliability-centered maintenance, the total-productive maintenance and risk based maintenance:

- **Reliability centered maintenance.** This technique is used to optimise the practices of the maintenance strategy in order to prevent the reliability level of the system from dropping below a certain specified value at any means.[26,1] This approach is based on achieving a level of reliability for the items/parts required at any maintenance cost. This technique is employed for items/parts that are critical for the operation of the system, or their failure could result in catastrophic system failure or high loss of revenue.

- **Total productive maintenance**. This technique is a critical addition to lean production, where the maintenance tasks and operations are designed to achieve the desired goal, e.g. high production or low cost.[1,3,24] This maintenance optimisation is based on a combination of preventive maintenance actions and continuous efforts to modify and redesign equipment and techniques with a goal to increase flexibility in processes and promote higher yield in production.[1]

- **Risk based maintenance.** It aims at reducing the overall risk of failure of the operating facilities. In areas of high and medium risk, a focused maintenance effort is required, whereas in areas of low risk, the effort is minimized to reduce the total scope of work and cost of the maintenance program in a structured and justifiable way.

2.2.2 Maintenance practices for offshore structures

When considering offshore structures, e.g. oil rigs and offshore wind farms, which are located in the marine environment where the accessibility is restricted to times of good weather and where the cost of maintenance tasks are vastly increased because of the remote location, then the maintenance practices depend on whether the project is manned or unmanned.[27]

Considering manned offshore structures, i.e. there is a permanent maintenance team on the structure, then item failures can be detected and repaired quickly, conversely when considering unmanned offshore structures, then the maintenance team has to be transported from the shore together with appropriate spares. Clearly the transportation depends on the weather and sea state and availability of resourses and in any case each trip will be costly, e.g. in the North Sea region some offshore platforms are inaccessible for long periods of time between October and April, due to weather and sea state conditions.[28] Considering offshore wind farms which are unmanned structures, then the optimisation of maintenance strategies is required to minimise the maintenance costs that incure for transporting maintenance teams and spares, in order to achieve competitive prices for the produced electricity.[29]

Considering an offshore oil rig, where a failure in a critical item could result in the production plant to stop operating, the lost revenue when being in a breakdown state is so high that any maintenance expedition cost could be justified to bring the offshore oil rig back in operation, which indicates that a reliability-based optimisation technique is often employed to establish the maintenance strategy for offshore oil rigs, where maintenance expenditure is of lower priority, as compared to critical item reliability. On the other hand, when considering offshore wind farms, the risk of total project breakdown is reduced, as compared to oil rigs, since the production of energy is achieved by a number of wind turbines and the failure in one of the wind turbines does not affect the production of energy from the other wind turbines, which indicates that the cost of maintenance expeditions is a key parameter to consider for offshore wind farms, as compared to offshore oil rigs.

Considering the observations made in the previous paragraphs on the definitions of maintenance strategies, their optimisation techniques and the maintenance challenges for offshore structures, then the possible maintenance strategies for offshore wind farms are listed below:

1. **No maintenance strategy**: Neither preventive nor corrective maintenance are performed on the offshore wind turbines but only major overhauls are performed between long periods of time, e.g. 5 years. This maintenance strategy could be a possible solution when the failure rates of offshore wind turbines are very low. Considering the current reliability of existing offshore wind turbines, as presented in Appendix E, this strategy can not yet be implemented; it could only form a possible solution for future highly reliable offshore wind turbines.

2. **Corrective (breakdown or reactive response) maintenance strategy**: Repairs are carried out after an offshore wind turbine has failed, where the maintenance expeditions are initiated immediately provided weather and sea state conditions permit them. This maintenance strategy is the present practice adopted for existing offshore wind farms.

3. **Periodic maintenance or planned intervention maintenance policy**: Fixed dates are set at the duration of the operational year of the offshore wind farm, when maintenance personnel are transferred to the offshore wind farms to repair, replace or inspect the wind turbine components. Preventive and predictive maintenance practices could be integrated into this strategy. Offshore wind turbines could be monitored for their condition and statistical reliability tools are used to preventively maintain or exchange critical items before any failure occurs. The specific periods for the planned maintenance expeditions could depend on different parameters of offshore wind farms, e.g. weather and sea state conditions, accessibility levels, availability levels, or reliability of wind turbines.

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2.3 A review of O&M practices for offshore wind farms

It is reported that for offshore wind farms the O&M costs account for typically 23% of the project's total expenditure as summarised in Table 2.1 and Figure 2.1, or alternatively this may be expressed as accounting for between 25-30% of the cost of unit of energy produced.[9,30,31,32,33,35] For an equivalent onshore project, the O&M costs as a percentage cost of the energy is estimated to be between 5-10%.[34] The main reason for such a difference may be attributed to the impact of operating a wind turbine in the marine environment where the wind turbines are 'stressed' in a harsher maritime environment and their accessibility for maintenance restricted by weather and sea-state conditions, and also by their distance to shore which affects accessibility, meaning maintenance expedition to offshore wind turbines tend to be more costly than visits to onshore wind turbines.

Table 2.1 Major cost components of an offshore wind farm.[33] The installation and decommissioning for the Opti-Owecs project has been included in the other subcategories, excluding the O&M.

Component	% of energy cost (Opti-Owecs)	% of installed cost (Owecop)
Turbines and tower	34	25
Sub-structure and foundation	24	11
O&M	23	17
Electrical interconnection	15	17
Installation and decommissioning	included above	18
Other	4	12

The current O&M practice adopted for existing offshore wind farms is reactive response. Essentially, when an item fails and the wind turbine becomes non-operational a maintenance expedition is launched at the first opportunity to carry out the repair, this being an additional visit to the wind turbine over any planned routine preventive maintenance visit. Failed items are generally repaired in situ or by exchange so the corrective maintenance strategy ensures the wind turbine is returned to full operational state as quickly as practically possible. The corrective maintenance strategy for offshore wind farms has been adopted from the offshore oil rig industry and additionally has also adopted a reliability-based optimisation technique to increase the energy harness.

The corrective maintenance strategy has been applied to the offshore wind farms since early development, the reason being the fact that the first offshore wind farms were prototype projects that tested the wind turbine technology in the marine environment, consisted of a small number of wind turbines, located very close to shore,[10,12] and the necessity to show high energy harness was required, in order to attract further funding for the future, which resulted in high numbers of maintenance expeditions, as explained in the following paragraphs. These maintenance practices have been adopted for all the existing offshore wind farms.

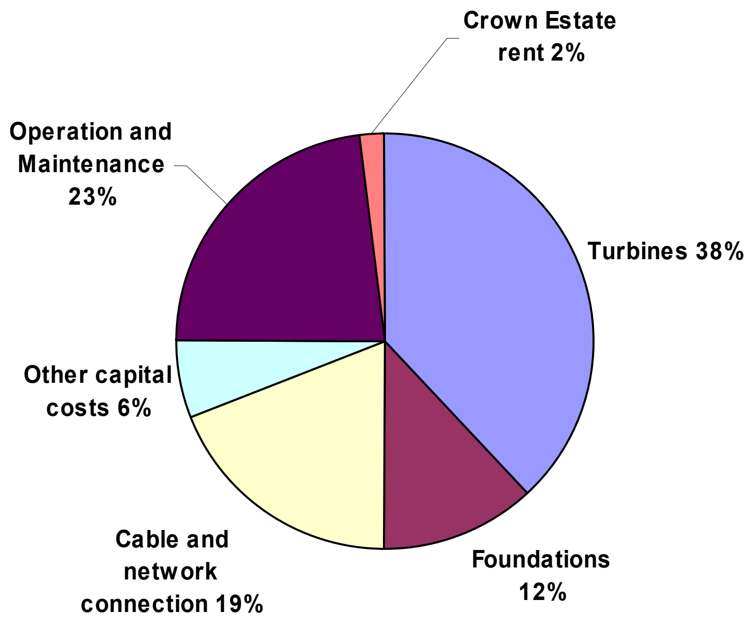

Figure 2.1 Average Offshore wind farm cost breakdown (Values obtained from 7,14,34)

This approach to maintenance for offshore wind farms is shown, in the following literature survey, to be effective in maintaining high levels of availability, whilst found to be expensive because the majority of offshore wind turbine failures and weather dependant accessibility are unpredictable, as explained further in this chapter, and it is costly to initiate and carry out repairs especially at short notice.[3,31,32] In contrast, the corrective maintenance strategy is reported as being a suitable strategy for onshore wind turbines, where remoteness has much less impact on accessibility and is largely unaffected by weather and the availability of specialist transport, e.g. ships and helicopters. Investigations reported in this thesis indicate that the corrective maintenance strategy could potentially not be practical nor effective for large offshore wind farms when the cost of electricity generation must be competitive primarily because access is dependent upon environmental conditions, i.e. weather and sea state. O&M costs have been shown in Figure 2.1 to account for a large percentage of the price of energy produced by offshore wind farms, therefore reducing the maintenance costs could result in greater competitiveness of electricity generated by offshore wind turbines in the electricity market.

A literature survey of the operation and maintenance aspects of offshore wind farms has been conducted to review and identify the technical challenges of O&M processes that large remote offshore wind farms could possibly face. The following notable studies are relevant to the argument that there is a need for a re-evaluation of O&M strategies for offshore wind farms.

Van Bussel (1997)[10] in a project funded by the EU to assess the current practices on O&M strategies in offshore wind farms, concludes that the unplanned events for repairs and maintenance of failed wind turbine components accounts for a significant percentage of the maintenance tasks, typically between 50-70%, and that the maintenance strategy applied to existing offshore wind farms is reactive response with regular preventive maintenance tasks, e.g. lubrications and inspections, being carried out once or twice a year. The study also concludes that the cost of maintenance of offshore wind farms is much higher than equivalent onshore wind farm projects, and the reliability is highly affected by the marine environment, indicating that a different approach to the maintenance strategy is needed that diverts from the existing maintenance practices and a technical re-design for the offshore wind turbines is essential to achieve a financially viable project for large offshore wind farms.

Similar findings are made by van Bussel and Henderson (2001)[13] in a project funded by the EU to assess the maintenance practices for offshore wind farms, which concludes that the marine environment and the accessibility difficulties have resulted in higher cost for maintenance tasks when employing the corrective maintenance strategy, as compared to the costs associated with maintaining onshore wind turbines. The study suggests that an optimisation of the accessing methods and transportation means to offshore wind farms is essential, in addition to an optimisation of maintenance practices in order to comply with the harsh marine environment for existing and future offshore wind farms. This study also emphasises the need to diverge the maintenance strategy of offshore wind farms from the conventional maintenance practices of onshore wind farms, therefore supporting van Bussel (1997)[10] views discussed in the previous paragraph.

Musial and Butterfield (2006)[35] review the recent status of offshore wind farms and provide a perspective in the critical parameters affecting the future development of offshore wind farms. The study suggests that much of the success of onshore wind turbines can be attributed at the ability of designers to reduce capital costs of onshore wind turbines and maintaining acceptable levels of reliability, while recognising that onshore wind farms benefit from ease of accessibility so the corrective maintenance strategy can be adopted to ensure revenue is maximised. The study also suggests that since onshore wind farms fundamentally benefit from accessibility levels close to 100% along with the desire to keep initial project cost low, has lead to neglect an added capital investment to reduce long term O&M costs. When considering offshore wind farms however, the authors explain that O&M work at sea is significantly more challenging, more time consuming and more costly. They conclude by suggesting the corrective maintenance strategy has not yet shown itself to provide the best economic solution for offshore wind farms. The conclusions of this study also indicate the need for the development of new maintenance strategies for offshore wind farms that will take into consideration the effect of the marine environment.

Kooijman et al (2004)[37] review the current situation in offshore wind industry in the North Sea, with respect to maintenance strategy and wind farm power losses. This study suggests that the corrective maintenance strategy, as currently applied to offshore wind farms, has led to over-maintenance strategies, due to the effect of the marine environment, which has resulted in increased maintenance costs. The study suggests that the corrective maintenance strategy is a major factor when explaining why offshore wind farms are economically uncompetitive when compared against onshore wind farms. The authors suggest that an increase of wind turbine reliability is needed to maximise revenue and conclude that the optimisation of the offshore wind farm O&M strategy is needed to improve competitiveness so large scale offshore wind energy projects may compete successfully in a liberalised European energy market. The study concludes that a development of an optimised preventive maintenance strategy for offshore wind farms could potentially minimise the maintenance expedition costs, through the use of statistical data on offshore wind turbine failure rates.

Andrawus et al (2007)[38] attempts to analyse the maintenance practices for offshore wind farms by modelling wind turbine failures and investigating maintenance practices of the corrective maintenance strategy. This study also suggests that the existing maintenance practices of offshore wind farms are found inadequate for future applications, this being explained by the fact that the impact of wind turbine failure consequences on revenue generation limits the adequacy of existing maintenance strategies to achieve electricity at competitive prices. The study suggests that effective implementation of maintenance optimisation will improve the reliability and availability of wind turbines, while it will reduce the overall cost of operation and maintenance by revealing and focusing attention on critical areas. This approach could potentially facilitate elimination of root causes of wind turbine failures and also maximise the overall return on investment in wind farms. The study suggests that carrying out maintenance activities, i.e. repairs, inspection, preventive maintenance, and replacement of items more frequently, increases the direct cost of maintenance, which in turn results in reduction of the risk exposure or the consequences of not performing maintenance activities as required, however, the less frequent the maintenance activities, the lower the maintenance cost, and the higher the risk exposure. The optimisation of existing maintenance practices for offshore wind farms should deal with the interaction between these factors and aim to determine the optimum level. The study summarises that the existing maintenance practices of offshore wind farms have to be optimised by considering the failure rates of wind turbines in the marine environment and the costs associated with maintenance expeditions, which should result in designing a maintenance strategy that aims to produce energy at competitive prices. The conclusions of this study also indicate the need for optimisation of the existing maintenance practices for offshore wind farms by introducing proactive maintenance tasks that could minimise the economic risk exposures to high wind turbine failure rates and produce energy at competitive prices.

Similar suggestions are made by McMillan and Ault (2008)[39] who study the impact of offshore wind turbine reliability levels on investment payback period and maintenance practices by identifying key parameters that affect the offshore wind farms, e.g. capacity factor. The study emphasises the unique nature of O&M practices for offshore wind farms that is quite different from other power plants in the sense that marine weather conditions, large distance from shore, accessibility difficulties and the number of wind turbines, highly complicate the maintenance expeditions and increase the O&M costs. The study also concludes that future offshore wind farms are expected to be further offshore to attract higher wind speeds and consisted of a large number of wind turbines, which could result in new challenges faced in terms of O&M practices, and that traditional maintenance approaches, i.e. corrective maintenance strategy, may not necessarily be effective and efficient. The study also suggests that a shift to a cost-optimal time-based maintenance strategy could potentially be more effective, i.e. a planned/scheduled maintenance where the intervals between maintenance expeditions are defined by the cost reduction in energy produced from offshore wind farms.

Sorensen (2009)[40] describes a risk-based approach for planning maintenance of offshore wind farms where inspections and remote condition monitoring are used to determine the maintenance approach to wind turbines. This study suggests that the costs associated with the corrective maintenance strategy for offshore wind farms is substantial, as compared to onshore wind farms, and will possibly increase when considering future offshore wind farms, due to the effect of the marine environment, distance to shore and water depth. The study also suggests that a shift to a proactive maintenance strategy that could implement regular inspections to low reliability items could potentially reduce the maintenance costs for existing and future offshore wind farms, where the time between inspections and predictive maintenance tasks being defined by the failure rates of the wind turbine components. However, the effect of reduced accessibility and the effect of weather and sea state conditions have not been considered in this study, which could potentially be a further factor that could limit the number of regular inspections and maintenance tasks of critical items and could define the specific time in year when these tasks could be performed more effectively. However, this study also emphasises the need to mitigate from current maintenance practices of offshore wind farms to a proactive maintenance strategy.

Hau (2006)[41] suggests that in order to limit the complex and expensive work at sea then a preventive maintenance strategy should be a key objective when considering the maintenance practices of offshore wind farms. The author reports that the reason the energy produced from offshore wind farms is not achieved at competitive prices, as compared to onshore equivalent wind farms, is explained by the effect of the marine environment on the maintenance practices and wind turbine reliability. The author emphasises the need for further research in different maintenance practices for offshore wind farms which should take into consideration the effect of the marine environment and possibly employ preventive maintenance practices.

The summaries of notable publications given in the previous paragraphs suggest that the O&M strategy is a significant factor to be considered when evaluating the economic viability of large offshore wind farms. The O&M practices to offshore wind farms has been adopted from the onshore wind farm practices, which have been optimised by considering the maintenance of offshore oil rigs, this being explained by the attempt to achieve high energy harness.

Further, it has been identified from the reported studies that the O&M processes of offshore wind farms are compromised by weather and sea-state conditions, wind turbine failure rates, and reduced accessibility, while their distance to shore and water depth cause an additional challenge and expense. These conclusions indicate that their effect on the corrective maintenance strategy has resulted in over-maintenance practices for offshore wind farms, which in turn negatively affects the unit cost of energy produced. For example, consider a bearing failure that causes an offshore wind turbine to stop operation, when employing the corrective maintenance strategy. The bearing would be repaired or replaced and the wind turbine returned to service as quickly as possible, with only a modest attempt, if any, being made to determine the root cause of failure, which could prevent a reoccurrence, which results in increased maintenance visits. The authors view is that it is a paradox that the greatest winds are available in open water at sea yet it is this environment which posses the greatest challenge to achieve high reliability and for the O&M of offshore wind turbines. A general conclusion reached in much of the published work is that the corrective maintenance strategy is unlikely to be economically attractive for future large and remote offshore wind farms because significant maintenance resources will be needed for the maintenance of the wind turbines which would not be effectively utilised unless a maintenance optimisation is introduced, while the complex and expensive work in the marine environment could potentially increase the cost of energy produced and different maintenance practices should be adopted to address this challenge.

Furthermore, the studies that have been reviewed conclude to the fact that an optimisation of the existing practices of the maintenance strategy of offshore wind farm is required, while a shift to proactive maintenance strategies is suggested that could potentially employ both preventive and predictive maintenance practices. Scheduled maintenance expeditions that employ regular inspections and preventive maintenance to critical wind turbine components and predictive maintenance practices that prevent occurrence of failures could potentially result in a decrease of the maintenance costs for offshore wind farms. An alternative O&M strategy to the current practices for offshore wind farms that employs these proactive maintenance practices is the planned intervention maintenance policy, which may be suitable when considering the O&M of significant numbers of wind turbines in large offshore wind farms. A planned intervention maintenance policy adopted for offshore wind turbines could potentially offer greater effective use of maintenance resources and therefore be more economically attractive, however a compromise is needed with increased downtime (as turbines await their turn for repair) reducing revenue against reduced O&M costs. The reliability of the offshore wind turbines is an important factor to consider when balancing costs and revenues, as has been concluded in much of the studies reviewed in the previous paragraphs.

A planned intervention maintenance policy for offshore wind farms would involve scheduling visits to each wind turbine at specified times across the year with the scheduled visits being largely determined by the reliability of the wind turbines and the weather conditions, as suggested by much of the studies reviewed earlier in this paragraph, i.e. statistical wind turbine reliability data could be used for predictive maintenance practices to determine the scheduled maintenance visits, while weather related accessibility issues should be considered to prevent unplanned postponing or cancelling of scheduled maintenance visits, as is currently happening when considering the corrective maintenance strategy practices. An offshore wind farm using a planned intervention maintenance policy, would mean each wind turbine receiving as many visits as necessary to maintain its availability above a specified level which itself is determined by considering the economics. The required availability level should be determined by balancing the maintenance resource costs e.g. manpower, transportation means (ships and helicopters), etc and the cost of downtime, i.e. the loss of revenue from the sale of electricity.

Planned intervention is a maintenance strategy whereby maintenance periods are planned to occur at particular times so that there are fixed intervals between each maintenance periods. This means that should wind turbines become non-operational between the planned intervention times will remain non-operational until the next planned intervention occurs. Wind turbines functioning correctly will be preventively maintained at the next scheduled maintenance visit regardless. The planned intervention maintenance policy means that repairs and maintenance will effectively occur at the same time – at a time planned in advance therefore allowing optimal use of maintenance equipment and resources.

The planned intervention maintenance policy for offshore wind farms should be designed to address the key parameters that affect the economics of the project, e.g. weather and sea state, reduced accessibility and wind turbine failure rates, as has been suggested by much of the studies reviewed in the previous paragraphs. A literature review is conducted in the following paragraphs in order to identify the key parameters that affect the economic viability of offshore wind farms and the important variables that need to be considered when designing a planned intervention maintenance policy.

2.3.1 A review on the parameters affecting the offshore wind farm O&M strategy

It is concluded from the literature review on maintenance strategies in the previous paragraphs that the maintenance strategy that has been adopted so far for the offshore wind farms was based on over-maintenance practices to keep the wind farm availability at high levels to maximise energy output, at the expense of high maintenance costs. A planned intervention maintenance policy has been proposed by the author as a possible solution to this technical challenge of maintenance of large offshore wind farms. An O&M model for offshore wind farms should be developed to simulate a planned intervention maintenance policy in order to quantify the possible benefits on the economic viability of offshore wind farms, when compared against the current maintenance practices. The parameters that affect the accessibility, availability and maintenance of offshore wind turbines, which in turn affect the outputs of an offshore wind farm, e.g. energy output and cost of unit of energy produced, have to be identified and implemented in the development of the planned intervention maintenance policy model. A critical review in the available literature is conducted in the following paragraphs to identify the existing models on O&M practices of offshore wind farms which simulate the different parameters that affect offshore wind farms and an investigation is conducted to determine their suitability for the simulation of planned intervention maintenance policy.

Rademakers et al (2003)[42] investigate the factors affecting the O&M practices and costs when considering a corrective maintenance strategy for future offshore wind farms. The authors have developed an economic and an energy model to calculate the unit cost of energy produced, and report that when estimating the O&M costs of offshore wind farms then the effect of the following parameters on the cost of unit energy produced should be considered:

- The size and the reliability of the offshore wind turbines.
- Operation and maintenance strategy adopted for the project.
- Distance to shore.
- Accessibility and transportation means.
- Water depth.
- Capacity factor.
- Size and orientation (micro-sitting) of the wind farm.
- Weather and sea state.

The study reports that all these parameters have to be simulated when developing an O&M model of the corrective maintenance strategy for offshore wind farms. The study suggests that a stochastic approach to the weather conditions is yet to be considered, since a deterministic approach would not yield accurate results, while the preventive maintenance of wind turbines has not been taken into consideration in the developed models. However the economic and energy models that have been developed in this study are based on a deterministic approach of wind turbine failure rates, which indicates that the results of the study are based on incomplete models and further investigations are needed to quantify the effect of the variability of the wind turbine failure rates on the cost of unit energy produced. On the other hand, the economic model developed in this study is a good step towards the simulation of the costs incurred during the operation of an offshore wind farm, whilst the costs for scheduled maintenance and repair tasks for the planned intervention maintenance policy would require a different simulation approach.

Jacquemin et al (2007)[43] examine the interdependencies between key parameters of O&M practices of offshore wind farms, i.e. transportation means, accessing methods, and number of maintenance personnel. The study suggests that the O&M of offshore wind farms is inherently multi-variant and multi-criteria and the authors promote the idea of developing new tools to help quantify the various O&M strategies to mitigate economic risks and that these risks are mainly related to adverse weather conditions, poor reliability, reduced accessibility and the cost of specialised equipment required for certain O&M operations offshore, which in turn affect the cost of energy produced.

Krokoszinski (2003)[44] develops an energy model to calculate the energy produced by offshore wind farms when considering a corrective maintenance strategy. The model takes into consideration the energy losses due to wind turbine failures, downtime and maintenance tasks, whilst adopting onshore failure rate data without considering the effect of the marine environment on the reliability of offshore wind turbines. The energy model that is developed in this study is a significant step towards quantifying the effects of the energy output on the economic viability of the wind farm, while the author concludes that the development of an energy model for offshore wind farms greatly depends on the maintenance strategy adopted, which indicates that a different energy model should be developed when simulating a planned intervention maintenance policy, as compared to the energy model of the corrective maintenance strategy explained in this study.

Elkinton et al (2006)[33] investigate different factors that affect the offshore wind farm layout optimisation and suggest that not only a wind wake model is required when considering the wind farm layout but also a model that simulates the O&M practices and availability of the wind farm. The authors emphasise that no complete models of offshore wind farm O&M costs has been found in the literature, that take into consideration and simulate all the different aspects of offshore wind farms, e.g. the wind turbine failure rates, wind farm availability and maintenance practices. The study uses a simple economic model to calculate the maintenance costs and concludes that the model yields results that when compared to industrial data are found to be significantly off scale, the reason being the lack of a complete economic model for offshore wind farms in available literature. The study emphasises the need for the development of an economic model that considers the O&M costs of offshore wind farms and assesses the offshore wind turbine reliabilities and offshore wind farm availability.

Andrawus et al (2006)[45] describes a methodology for selecting suitable maintenance strategies for onshore wind turbines using a hybrid reliability based maintenance optimisation and asset life cycle analysis techniques. Condition based maintenance tasks (predictive maintenance strategy) are identified using a developed model and compared against the results obtained from time based maintenance tasks models (preventive maintenance strategy), by determining wind turbines failure modes and causes and expressing them to financial terms. The condition based maintenance strategy necessitates the use of advanced monitoring systems and the time based maintenance strategy involves carrying out preventive maintenance tasks, e.g. inspections and repairs, at predetermined regular intervals, as previously explained in this Chapter. The study shows that the comparison of the net present value (NPV) economic model is not absolute for a valid decision making over the O&M strategy since it considers only financial criteria, while the maintenance strategy of wind farms depends upon failure characteristics of the wind turbines, therefore a more complex economic model is yet to be developed. The authors report that the results of the study show that the condition based maintenance is the most cost effective option as compared against the time-based maintenance practices for onshore wind farms. The conclusions reached in this study are important for the investigation of O&M strategies of onshore wind farms and point out the inadequacy of a simple economic model, i.e. NPV model, while emphasise the need for a dedicated economic model that takes into consideration the variability of the failures of wind turbines, which generates the need for further analysis and examination in the subject. However, this study was based on models that considered failure modes and input parameters of onshore wind farms, where the total advantages of time based maintenance could not be revealed. The models developed in this study are found to be limited to onshore wind farms that benefit from accessibility levels close to 100%, whilst when offshore wind farms are considered, the marine environment and reduced accessibility will affect the output parameters differently and could possibly lead to different results, as compared to onshore wind turbines, as explained by Tavner et al (2006)[46] in the following paragraph.

Tavner et al (2006)[46] review existing reliability data of onshore wind turbines from Danish databases and assesses the influence of weather and in particular the wind speed on failure rates. After investigating the relationship between the periodicity of wind data and the periodicity of failure rates the study suggests that there is a clear relationship between the two elements. The study shows that the reliability of offshore wind turbines is affected by higher wind speeds and when conducting a reliability analysis for offshore wind farms this factor has to be taken into consideration. The study emphasises the need to integrate the effect of the marine environment, e.g. higher wind speeds and humidity, into the reliability of offshore wind turbines for the development of the O&M model.

Obdam et al (2007)[47] develop a computer based model to estimate the operation and maintenance costs of offshore wind farms when using the corrective maintenance strategy. The study suggests that when modelling O&M practices of offshore wind farms then the reliability of the wind turbines is a key parameter that will affect the outputs of the project, i.e. energy output and cost of unit of energy produced. The authors develop a reliability model, i.e. a model that quantifies the failures of offshore wind turbines and identifies the repair time for each identified failure, using onshore wind turbine failure rate data, whilst no consideration is made on the effect of the marine environment on the reliability of the wind turbines, as emphasised in the previous paragraph by Tavner et al (2006).[46] The study suggests that when simulating the O&M of offshore wind farms further parameters are still to be modelled, e.g. the wind turbine component downtime and the effect of the marine environment on accessibility and availability of the wind farm. This study emphasises the need for a wind turbine reliability model to be investigated into the development of the O&M

model that considers not only failure rates but also the effect of downtime and the marine environment on the economics of offshore wind farms.

Van Bussel and Bierbooms (2003)[12] investigate the effect of different transportation means to future offshore wind farms on the availability and the economics of the project by considering maintenance personnel safety, weather-windows for repairs and wind turbine failure rates. The study reports that the cost of maintenance transportation means for offshore wind farms is a key parameter that significantly affects the economics of the project. The authors develop a model to simulate the O&M practices of a corrective maintenance strategy and suggest that a stochastic approach is required to simulate the weather conditions and the variability of the failure rates of wind turbines, since a deterministic approach would not give accurate results. On the other hand, the wind turbine failure rates used in the study are extracted from onshore wind farm data, and the effect of the marine environment on the offshore wind turbine reliability has not been considered, as previously suggested by Tavner et al (2006).[46]

Zaaijer and Van Bussel (2002)[48] develop an offshore wind farm O&M model to review the different design and installation approaches to offshore wind turbines. The study develops an economic model and an energy model to calculate the unit cost of energy produced from offshore wind farms when using a corrective maintenance strategy. The study reports that with the lack in literature of a detailed reliability model of offshore wind turbines it is difficult to accurately determine the availability levels of offshore wind farms and thus to accurately calculate the cost per unit of energy produced. The models developed in this study are a good step towards the simulation of current maintenance practices of offshore wind farms, whilst the stochastic behaviour of failure rates has not been addressed by the developed model, however a different approach should be considered for a planned intervention maintenance policy, as previously suggested by Krokoszinski (2003).[44]

Negra et al (2007)[49] investigate the key aspects that affect the offshore wind farm availability and wind turbine reliability, and develop a stochastic model to simulate different parameters, i.e. wind speed variability and its effect on the reliability of wind turbines, while considering wind wake effects and wind turbine hub height variability. The authors emphasise the use of a stochastic model to simulate the wind turbine reliability in order to take into consideration the variability of different parameters and reports that a deterministic approach to the model would not yield accurate results, since the parameters would have to be controlled into fixed values. The authors suggest that stochastic models are yet to be developed in order to also take into consideration the variability in other parameters that affect the reliability of offshore wind turbines, i.e. the marine environment and higher wind speeds when compared to onshore wind farms, as previously suggested by Tavner et al (2006).[46]

Tavner, Xiang and Spinato (2006)[50] explain a reliability modelling technique to predict the life curves of wind turbines by analysing the failure rates of onshore wind turbines. The study summarises that the developed model could be applied to offshore wind turbines, but further research is needed on the effect of the marine environment on offshore wind turbine failure rates.

The summaries of notable publications given in the previous paragraphs on modelling the O&M practices of offshore wind farms and the factors that affect their economic viability, suggest that the O&M costs is a significant factor to be considered for the modelling of maintenance strategies. O&M costs are in turn primarily affected by the reliability and downtime of offshore wind turbines, accessibility of offshore wind farms, the cost of transportation means, the distance to shore and the wind turbine system configuration. It has been pointed out in the studies reviewed in the previous paragraphs that when simulating the maintenance practices of offshore wind farms a number of different models are required, i.e. economic, energy and reliability models, in order to simulate the outputs of the project, e.g. energy output and cost of unit of energy produced, while it is suggested that these models greatly depend and should vary between different maintenance practices, which indicates that a different approach to the existing models should be considered for a planned intervention maintenance policy. A general conclusion reached in much of the published work is that when simulating the

O&M practices of offshore wind farms then the key parameters that affect the economics of the project have to be modelled by taking into consideration the effect of the marine environment, which is lacking in the existing models for the failure rates of offshore wind turbines. It can be concluded that the following models for offshore wind farms are still to be developed when considering a planned intervention maintenance policy:

- An O&M model for simulating the maintenance practices of a planned intervention maintenance policy for offshore wind farms.

- An energy model that calculates the energy output for the O&M model of a planned intervention maintenance policy, that considers the failure rates of offshore wind farms.

- A reliability model that considers the effect of the marine environment and the variability of the failure rates and time to repair of offshore wind turbines, which could define the number of scheduled maintenance visits for the O&M model of the planned intervention maintenance policy.

- A detailed economic model for offshore wind farms when simulating a planned intervention maintenance policy that takes into consideration all the different parameters that affect the economic viability of the project.

2.4 A review of CO2 emissions from offshore wind farms

As of year 2000 the greenhouse gasses related to power plants account for 24% of the total world emissions, as seen on Figure 2.2, which is a significant percentage that the EU has targeted to reduce for its member states by 20% by 2020.[51] The exact amount of emissions saved depends on which fossil fuel power plants are displaced by wind energy. In most of Europe this is coal, a situation likely to continue for a few years yet.[52] The reason for this is that nuclear plants and combined cycle gas turbines almost all operate at high load factors, to cover base load.[8] Base is termed the minimum load on the system, usually between 20 and 40% of the peak load.[8,53] As wind energy has priority access to the grid, due to EU directives,[7,54] its output contributes to that of the base load power plant.

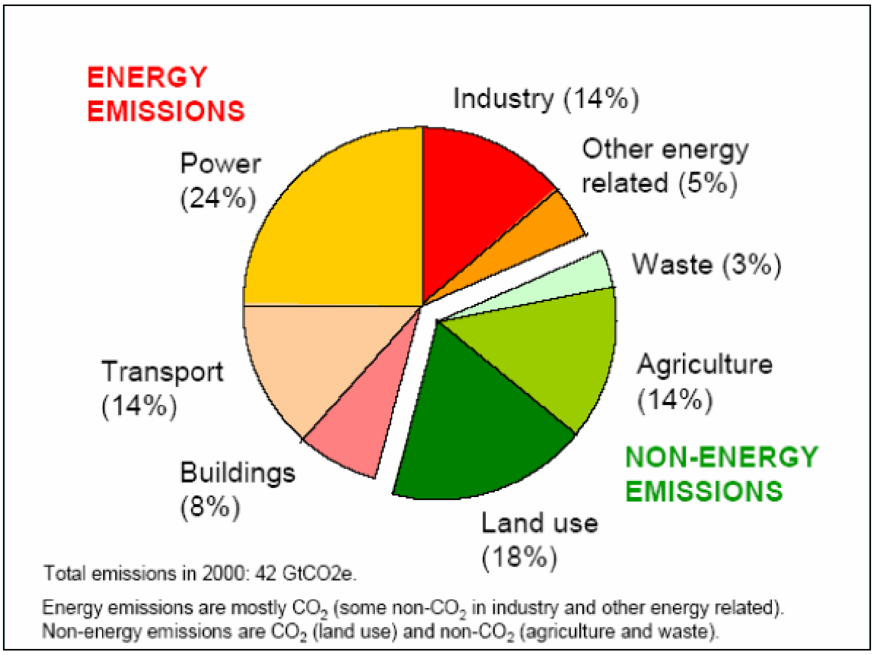

Figure 2.2 Greenhouse Gas emissions in year 2000.[51]

Table 2.2 CO2 emissions per kWh produced by different power plants.[107]

Power Generation Plant	Grams of CO2 emitted per kWh
Coal	815-990
Gas	356-653
Solar	50-95
Wind	5.5-37
Nuclear	6-26
Hydro	3-18

The use of wind energy therefore has the effect of displacing coal power plant and the greenhouse gas emission savings are those associated with coal power plant, currently around 900g/kWh of carbon dioxide, as shown in Table 2.2, plus oxides of sulphur and nitrogen and other chemicals.[8,55] For example, 10 GW of offshore wind farms, with a capacity factor of 30%, will therefore save around 23 million tonnes of carbon dioxide each year if coal power plants are displaced, plus substantial quantities of other harmful pollutants, e.g. NOx and SOx.[8]

In the wake of the Kyoto Summit on climate change, attention has been focused on ways to achieve global reductions in emissions of greenhouse gases. One of the principal ways that was suggested to achieve the reduction of CO2 is by development of renewable energy projects, however these projects and especially when considering the future offshore wind farms, then an amount of greenhouse gasses are emitted for the completion of the following processes:

- Component manufacture and wind turbine assembly;
- Wind farm installation;
- Operation and Maintenance; and
- Decommissioning of the project.

A literature review is conducted in the following paragraphs in order to identify the CO2 emissions associated for each of the above processes and investigate what further work is required for the calculation of the total CO2 emissions for offshore wind farms.

Jungbluth et al (2004)[56] describe the modelling of life cycle assessment for wind power with the aim of associating the CO2 emissions needed for the construction and installation processes of wind turbines. The study simulates by modelling a number of different variables, e.g. wind turbine power, size, location, capacity factor and materials associated, that the values of the CO2 emissions are about 11 grams per kWh produced for onshore wind farms and 13 grams/kWh for the offshore equivalent wind farms. The study also concluded that a 2 MW wind turbine causes higher emissions than a 800 kW one, and in both cases the largest contribution to the emissions is the material manufacture. However this study lacks the development of a model to simulate the CO2 emissions due to O&M processes for offshore wind farms.

Schleisner (1999)[57] examine the emissions related to the production and manufacture of materials for onshore and offshore wind farms using life cycle assessment models. The study concludes that for onshore wind farms the associated CO2 emissions is 9.7 grams per kWh of energy produced and for offshore wind farms is 16.5 grams/kWh. An important contribution of this study on the calculation of the CO2 emissions from wind farms is the incorporation of the decommissioning stage in the model; however it is also clear in this study that the CO2 emissions related to the O&M processes of offshore wind farms are neglected.

Pehnt et al (2008)[58] develop a comprehensive system to calculate the possible CO2 emissions reduction in the German power market by linking a life cycle assessment model of offshore wind utilisation with a stochastic model of the German electricity market. The study concludes that the resulting CO2 emissions reduction is in the order of 600 to 800 grams per kWh produced from offshore wind farms. However what has not been taken into consideration in this study is again the CO2 emissions associated with the O&M processes of the offshore wind farms for life cycle duration of 20 years of operation, which is anticipated to alter significantly the final results and show deviation from the resulting conclusions.

The summaries of notable publications given in the previous paragraphs on the calculation of the CO2 emissions from offshore wind farms suggest that when considering the manufacturing, the installation and decommissioning stages of offshore wind farms then the CO2 emissions could reach up to 16.5 grams per kWh produced, while it is indicated that the larger the power rating of the wind turbine the higher CO2 emissions should be expected and when considering future offshore wind turbines far from shore with significantly higher power rating, as compared to existing offshore wind turbines, then the associated CO2 emissions could be considerably increased.

However a general conclusion is reached when assessing the published work which is that the CO2 emissions during the operational stage of the offshore wind farm have been neglected. The transportation means for maintenance tasks to the offshore wind farms, e.g. helicopters and ships, have a significant contribution to the total CO2 emissions from the project and are directly related to the O&M strategy adopted and the reliability of the wind turbines. The literature review conducted in the previous paragraphs stretches out the need for a model to calculate the CO2 emissions during the operation and maintenance stage of offshore wind farms and investigate the results when using different O&M strategies.

2.5 Summary and Discussion

Undoubtedly the offshore wind power generation is now attracting greater attention but has a long way to go before it is fully commercialised and starts to produce energy at competitive prices, while considering the subsidies for wind energy that will not be maintained indefinitely. The evolution of the wind technology has seen many innovations since the first offshore wind farm was constructed, where each turbine's rating was 450 kW and in the near future plans to commercially install 6 and 7 MW wind turbines are made.[7]

The review of papers published on O&M processes of offshore wind farms has shown that this is an active area for research and there are some key points that can be summed up as follows:

- The current practices of O&M for offshore wind farms, i.e. the corrective maintenance strategy, has resulted in over-maintenance practices to demonstrate high energy harness at very high maintenance expense, which has negatively affected the cost per unit of energy produced.
- A general conclusion reached in much of the published work is that the corrective maintenance strategy is unlikely to be economically attractive for

future large offshore wind farms because significant maintenance resources will be needed.

- The optimisation of the existing maintenance strategy of offshore wind farms is an important factor that will affect the economic viability of future projects and needs to be carefully studied. This maintenance strategy optimisation heavily depends on the consideration of the marine environment and the reliability of offshore wind turbines.
- A shift to proactive maintenance strategies for offshore wind farms that could potentially employ both preventive and predictive maintenance practices is suggested in much of the reviewed studies in order to mitigate the economical risks of over-maintenance practices currently employed.
- A planned intervention maintenance policy that employs proactive maintenance practices has been proposed in this thesis by the author as a possible solution to the technical challenge of offshore wind farms that could potentially reduce the maintenance costs by a more effective use of the maintenance resources, which could result in a reduction of the cost of unit of energy produced.

From the review of papers published on modelling the O&M practices of offshore wind farms, some important conclusions could be summarised as follows:

- The O&M costs is a significant factor to be considered for the economic viability of offshore wind farms, which in turn is primarily affected by the reliability and downtime of offshore wind turbines, accessibility of offshore wind farms, the transportation means, the distance to shore and the wind turbine system configuration.
- For the simulation of the maintenance practices of offshore wind farms a number of different models have to be developed, i.e. economic, energy and reliability models, in order to simulate the outputs of the project, e.g. energy output and cost of unit of energy produced.

- The models that need to be developed greatly depend on the maintenance strategy adopted for offshore wind farms, which indicates that a different approach to the existing models should be considered when developing an O&M model for a planned intervention maintenance policy.
- For the simulation of the O&M model for offshore wind farms the effect of the marine environment on the reliability of the wind turbines should be considered, which is lacking in the existing reliability models.

Summarising the critical review of the CO2 emissions from wind farms some important conclusions could be reached:

- The world has shown great interest to the offshore wind farms as the leading potential projects to offset the greenhouse gasses emitted by the conventional power plants.
- It is pointed out from life cycle assessment studies that the CO2 emissions related to the manufacture, installation and decommissioning of offshore wind farms are between 13 and 16.5 grams per kWh of wind energy produced, which depends on the power rating of the wind turbines, the distance to shore and the water depth of the offshore wind farm.
- These CO2 emissions values have not taken into consideration the operation and maintenance stage of the offshore wind farms. Due to ships and helicopters used to carry out the maintenance practices, significant amount of greenhouse gases are emitted, which have not been calculated in the published literature.

Bringing the above literature review together then the following conclusions are drawn:

- It is clear that the offshore wind turbine of the future will face technical challenges to tackle when considering the O&M procedures, then would the proposed solution of planned intervention maintenance policy be a possible solution to the identified challenges?

- How can the effect of the marine environment on the reliability levels of offshore wind turbines be quantified?
- Due to global warming issues leading to CO2 emissions, the renewable energy sources have been the main target for substituting the use of fossil fuels to generate electricity. At this point a question is raised on how ‘Green’ will the future offshore wind farms be, as compared to onshore equivalent projects by taking into consideration the CO2 emissions for the maintenance and repair operations.

It becomes clear that answers to these hypotheses are neither easy nor straightforward. A deep analysis and investigation is needed in order to give satisfying answers for these questions, which form the basis of research of this thesis. The next step for the investigations of these hypotheses it to explain and design in detail the proposed planned intervention maintenance policy for offshore wind farms.

3 Planned intervention maintenance policy

3.1 Introduction

This chapter explains planned intervention maintenance policy as a possible solution to the technical challenge of offshore wind farm maintenance. The advantages and disadvantages of planned intervention maintenance policy are identified and compared against the current practices, i.e. corrective maintenance strategy.

Two different methods are used in this chapter to design the planned intervention maintenance policy and to analyse key performance parameters affecting the maintenance of offshore wind farms. The Life Cycle Cost Analysis (LCCA) technique is used to analyse the costs of developing an offshore wind farm and how these costs are interrelated, whilst the Structured Analysis and Design Technique (SADT) is employed to investigate the key parameters affecting the planned intervention maintenance policy.

3.2 Explanation of the planned intervention maintenance policy

Figure 3.1 shows common maintenance strategies employed, which can be divided into proactive and corrective maintenance. Corrective maintenance is a maintenance strategy that is initiated by equipment failure with the maintenance tasks being undertaken immediately or at the first opportunity to do so. Proactive maintenance can be subdivided into planned/scheduled maintenance and condition based maintenance. Condition based maintenance is initiated once wear levels have exceeded set limits, detected by a deterioration in performance that has been identified by inspection and/or using techniques such as vibration analysis. Planned or scheduled maintenance is a maintenance method that initiates servicing and repair of machinery at specified points in time and is independent of the machinery operating status between maintenance visits.

A planned intervention maintenance policy is a subset of proactive maintenance and could potentially employ planned/scheduled maintenance and/or condition based maintenance practices. During a planned/scheduled maintenance visit all failed items will be repaired or replaced and working items will be inspected or replaced; the replacement of working items having been determined by reliability analysis or adverse inspection findings, as used for the condition based maintenance. Exchanged items are returned for servicing.

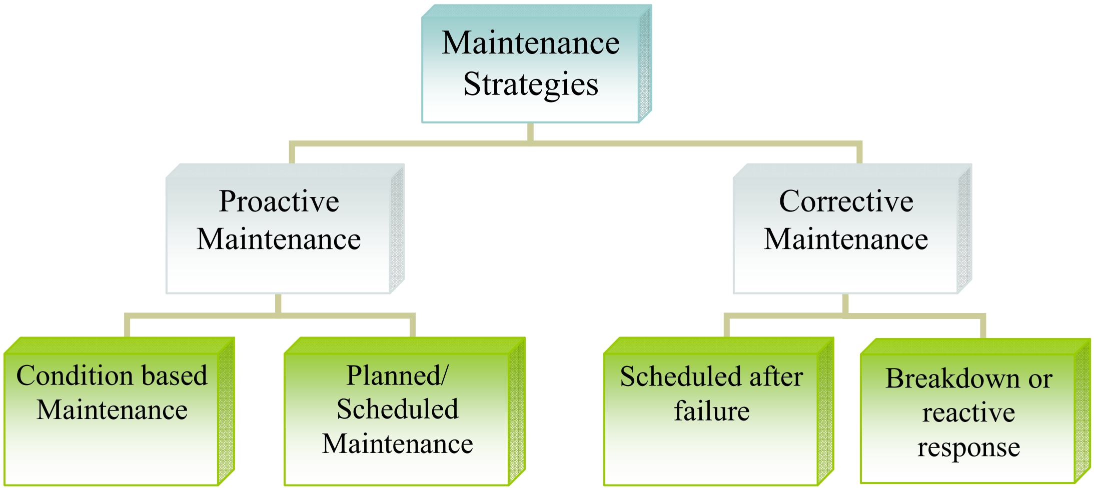

Figure 3.1 Maintenance strategy logic diagram[17]

Two examples of planned intervention maintenance policy are automobile maintenance and aircraft maintenance. Automobile maintenance is carried out at planned intervals which are determined either by mileage or time, typically 10,000 miles or 1 year. Items are serviced e.g. the engine, whilst other items are inspected with those determined to fail before the next scheduled maintenance being replaced e.g. brake pads.[59] Aircraft maintenance is also periodic determined by flying hours or time. To give an example, the Federal Aviation Administration (FAA) regulations dictate that all U.S. aircraft undergo different inspection and maintenance routines at varying intervals. In addition to the planned intervention maintenance policy automobile and aircraft would also be maintained using breakdown maintenance since their accessibility levels are high and it would be uneconomical not to do so.[60]

3.3 Suitability of planned intervention strategy for offshore wind farms

The O&M strategy adopted for offshore wind farms must ensure economic viability. Summarising the findings in Chapter 2, it can be said that there are three key decision drivers when selecting an O&M strategy for offshore wind farms:

- **Availability**. The aim is to ensure a high operational availability throughout the life of a wind farm. This was the key decision driver for early offshore wind farms in order to demonstrate high energy harness and thereby securing further funding for future developments,[12,13,10] and has remained the current practice. This driver may lead to over-maintenance which in turn directly affects the price of the energy produced, as detailed in Chapter 2, and may also result in greater levels of CO2 emissions occurring due to an excessive number of maintenance expeditions.

- **Energy Production Cost**. The aim of this driver is to set the cost of energy produced from a wind farm so that it may be economic in competitive energy markets. This should be the decision driver for future offshore wind farms because the current heavy subsidies are unlikely to be maintained indefinitely.[7,8] This driver may lead to a decrease in availability through a re-evaluation of the maintenance practices in order to drive the cost down.

- **CO2 Emissions**. 'Hidden' CO2 emissions from offshore wind farms occur due to the use of vessels and helicopters for the transportation of personnel and equipment for maintenance. At the present time such emissions do not feature in offshore wind farm analysis, however with larger numbers of high power offshore wind farms located further offshore expected to be in service in the future, such emissions will need quantifying. The maintenance strategy for future offshore wind farms should therefore be driven by also considering green house gas emissions due to maintenance practices. New maintenance practices may even be required to reduce the CO2 emissions.

For future offshore wind farms an O&M strategy is needed that should ensure energy production is at a competitive price with minimum ‘hidden’ CO2 emissions.

3.4 Comparison of planned intervention against reactive response strategy

The current O&M practice adopted for existing offshore wind farms is reactive response. When a component in a wind turbine fails, resulting in it becoming non-operational, then a maintenance expedition is launched at the first opportunity to carry out repairs. Failed items are repaired either in situ or by exchange. The maintenance strategy is therefore driven by the need to return the wind turbine to full operation as quickly as possible.[41] This approach to maintenance for offshore wind farms has been shown through experience to be effective but expensive.[41,61,62] In contrast, the corrective maintenance strategy has been reported to be a suitable strategy for onshore wind farms, where accessibility is not a determining factor.[45,41] Offshore wind farms are far more dependent upon environmental conditions, especially weather and sea state, which affect accessibility.[10,12,35]

For offshore wind farms, the corrective maintenance strategy has two primary factors that contribute to high maintenance costs; limited accessibility and limited time to carry out repairs.[10,12, 3,24] Limited accessibility occurs because access to offshore wind farms is heavily dependent upon the weather and sea state conditions, [10,12,35] which vary over the year, and upon the location of the offshore wind farm, i.e. the further from shore a wind farm is located the more difficult it tends to be to access.[41,61,62] Time to carry out repairs is dependent upon available weather windows, limited light conditions especially limited in the winter, and a generally more difficult working environment i.e. working at sea is more challenging than working onshore. As a consequence maintenance resources including manpower and equipment may not be utilised effectively.[41]

A consequence of limited time for repairs, is that maintenance tasks often tend to concentrate upon repairing failures with insufficient time being available to establish the root cause of the failure. For example, consider a bearing failure that causes a wind turbine to cease operation. With the corrective maintenance strategy, the bearing would be replaced and the wind turbine returned to service as quickly as possible, with only a modest attempt, if any, being made to determine the root cause of failure, which could prevent a recurrence. Inevitably, such maintenance practice may result in an increase in maintenance visits, thereby increasing costs.[63]

A planned intervention maintenance policy has not yet been adopted for offshore wind farms. This maintenance philosophy may, however, be suitable when considering the maintenance of significant numbers of offshore wind farms. For large numbers of offshore wind turbines the corrective maintenance strategy is likely to become economically unattractive, unless reliability levels of offshore wind turbines can be increased substantially, because significant maintenance resources will be needed. A planned intervention maintenance policy adopted for offshore wind turbines could potentially offer greater effective use of maintenance resources and be more economically attractive.

A planned intervention maintenance policy for offshore wind farms would involve scheduling visits to each wind turbine at specified points in time; the scheduled visits being determined by the reliability of the wind turbines and weather related accessibility. For example, an offshore wind farm using a planned intervention maintenance policy, would mean each wind turbine receiving as many visits as necessary to maintain its availability above a specified level. The required availability level should be determined by economics, which must balance the maintenance resource costs e.g. manpower and transportation means (ships and helicopters), and the cost of downtime i.e. loss of revenue.

However, in practice there are constraints which must be considered including weather conditions and sea state, the availability of vessels or helicopters to carry out the maintenance, lead time of spare parts for repairs, and the availability of manpower. Weather condition and sea state are highly dependent upon the location of the wind farm e.g. those wind farms far offshore are likely to be exposed to more adverse weather conditions and higher sea states. Furthermore, it generally becomes more expensive to maintain wind farms located further offshore simply because maintenance vessels and manpower are required for longer periods. Spare parts can be kept at hand but this requires additional inventory expenditure, whilst just-in-time delivery practices may leave the wind turbine inoperable should any delay occur in receiving the replacement parts.

3.5 Perceived advantages for planned intervention maintenance policy

Considering offshore wind farms, the perceived advantages of the planned intervention maintenance policy over the corrective maintenance strategy are:

- **Elimination of unplanned repair events**. Unplanned maintenance events account for a significant proportion of maintenance expeditions for existing offshore wind farms using the corrective maintenance strategy (typically between 50-70%).[10,64] The planned intervention maintenance policy deals only with planned events and by engaging advanced planning is able to effectively use maintenance resources. Unplanned events when using the planned intervention maintenance policy are simply ignored.

- **Sufficient time for repairs**. The corrective maintenance strategy limits the time available for standard maintenance tasks since priority is given to repairing the breakdown.[3,24] The planned intervention maintenance policy for offshore wind turbines would permit sufficient maintenance time for repairs and standard maintenance tasks. In the long term, this strategy could result in a reduction in the downtime e.g. machinery maintained in nearly new condition and not permitted to degrade beyond specified levels is more reliable and less likely to fail.[3,24,45]

- **Weather dependency**. The planned intervention maintenance policy allows scheduling of maintenance visits at periods of benign weather conditions and therefore avoids cancellations or postponing expeditions due to unexpected weather. For example, planned maintenance visits to offshore wind farms could be scheduled to occur only between May and October for the North Sea region, in accordance with weather and sea state data, e.g. as presented in Appendix C. The effect of weather on planned intervention maintenance policy could be minimised, which in turn could decrease maintenance costs.

- **Planning for transportation means**. The rapid development of offshore wind farms in recent years has resulted in a noticeable shortage of vessels suitable for installation and maintenance.[65,66,67] Despite a number of new purpose-built vessels being constructed to satisfy the short term needs of near future planned offshore wind farms, it is reported that there will be a shortage of vessels again in the future.[67] By planning the maintenance and repair tasks at specific points in time i.e. pre-booking of these expensive-to-hire purpose-built vessels, will secure their availability avoiding excessive rental charges whilst minimising wind turbine downtimes.

- **Reduced maintenance spare parts.** Corrective maintenance strategy usually results in the need to carry large inventories of the spare parts as it is difficult to predict when the parts will be needed.[3,24] For large scale wind farms this maintenance strategy could result in excessive stock holding costs that will increase the maintenance costs of offshore wind farms. On the other hand, the planned intervention maintenance policy use reliability levels and planned inspections to predict the need for spare parts. There are fewer ‘surprises’ and more spare parts can be purchased using just-in-time practice, which reduces the maintenance costs of the offshore wind farm.

- **Grouping failures together**. Considering the planned intervention maintenance policy then repairs and/or replacement of items and their planned inspection could be grouped together. One maintenance expedition could therefore be used to service multiple offshore wind turbines. On the other hand, there are time constraints (light conditions) and working constraints for safety reasons that may limit the number of wind turbines serviced per expedition.[10,4,35] Nonetheless, this advanced scheduling of the repair, replacement and inspection could result in reduction of maintenance resource costs and also reduce the CO2 emissions.

- **Optimisation of maintenance tasks**. In addition to the above, the maintenance tasks of the offshore wind farms can be designed to meet certain criteria that reduce the maintenance resource costs considerably. The maintenance vessels can be booked and scheduled for specific periods in Spring and Autumn, and the precise sequence of which wind turbines to be visited and the maintenance work to be performed can be determined by a combination of the following criteria:

    1. Scheduling by geographic proximity (to reduce the travelling time of the ships).

    2. The availability of wind turbine components planned for exchange (inventory).

    3. The developing history of the AMP (Asset Maintenance Plan) of the statistical mean time to failure of the wind turbine components, in a specific location.

- **Effective Asset Maintenance Plan (AMP)**. Considering the philosophy of planned intervention maintenance policy the reliability of the offshore wind turbines forms a key parameter for the improvement of the maintenance tasks from year to year. The development, implementation, and periodic evaluation of effective asset (wind turbines) maintenance plan are common techniques for a planned intervention maintenance policy. It involves obtaining the information on the reliability of the offshore wind turbines, necessary for establishing a dynamic maintenance program that improves upon the initial program, and its revisions, by systematically assessing the effectiveness of previously defined maintenance tasks. This results in optimisation of the maintenance strategy and reduces the maintenance resource costs. Monitoring the condition of critical or costly to maintain items by inspection could play an important role in the development of the AMP program.[3,24]

Designing an O&M strategy necessitates the clear understanding of key parameters affecting the total availability of the project, the cumulative energy output, the production cost of energy and CO2 emissions. These parameters are rather different than the ones affecting onshore wind farms due to their location in the marine environment resulting in a complex requirement in order to optimise the selected O&M strategy.

To identify an optimised O&M strategy for offshore wind farms it is necessary to break down the complex problem into its constituent parts using appropriate tools. Life Cycle Cost Analysis can be used to provide information about the economics of a wind farm project considering both capital expenditure (CAPEX) and operational expenditure (OPEX) which includes decommissioning costs. A Structured Analysis and Design Technique (SADT) can be used to break down the different phases when applying a maintenance strategy to offshore wind farms by determining the required resources e.g. manpower and equipment, when considering the various constraints e.g. weather and distance.

3.6 Life Cycle Cost Analysis

Life Cycle Cost Analysis (LCCA) can be defined as '*the total discounted cost of purchasing, installing, operating, maintaining and decommissioning a project over a defined period of time.*[68] Applied to an offshore wind farm project then life cycle costs appear to have three discrete stages, refer to Figure 3.2:[26,52]

a) The installation stage,
b) The service life stage, which includes energy production and maintenance,
c) The decommissioning stage.

The installation stage requires initial investment, with the costs incurred including all work done prior to the initial energy production day.[8,69] Such costs will include design costs, planning costs including licences, initial site renting costs, costs of the wind turbine foundations, sub-sea cabling and grid connection costs, material costs e.g. wind turbine sets and all assembly costs.[61,30,62] It is noted that O&M costs for onshore wind farms sometimes are included in the initial investment, but for offshore wind farms (and for the purpose of this study) the O&M costs will be considered as OPEX.[70,71,72,73]

The service life stage has two cost drivers; the operations costs and maintenance costs. The operations costs include the management and administration costs, the project insurance costs, public liability insurance costs, safety costs, cost of monitoring the project,[34,64] and the business rates and taxes.[69,34] Maintenance costs include spare item costs and stock holding, consumables for item maintenance e.g. gearbox oil, manpower costs and transportation costs.[26,13] The downtime costs are usually included in the maintenance costs, since the energy lost during major overhauls or extended maintenance periods affects the economics of the project.[74,34]

The decommissioning stage is the final stage of the project's LCCA. These costs will include the dismantling of the offshore wind turbines and their transportation back to shore for disposal or recycling so they will include manpower costs, transportation costs, disassembly costs and disposal costs. Since none of the existing offshore wind farms have reached the decommissioning stage, costs can only be estimated theoretically. However, what can be anticipated is that costs of decommissioning offshore wind farms will be higher than onshore wind farms, due to the marine environment.

Considering the economics of the offshore wind farms, then the CAPEX consists of the installation stage costs and the OPEX consists of the service life stage and decommissioning stage costs. When considering maintenance strategies for offshore wind farms, it is the OPEX which will be affected and to understand the relationship then a Structured Analysis and Design Technique can be used.

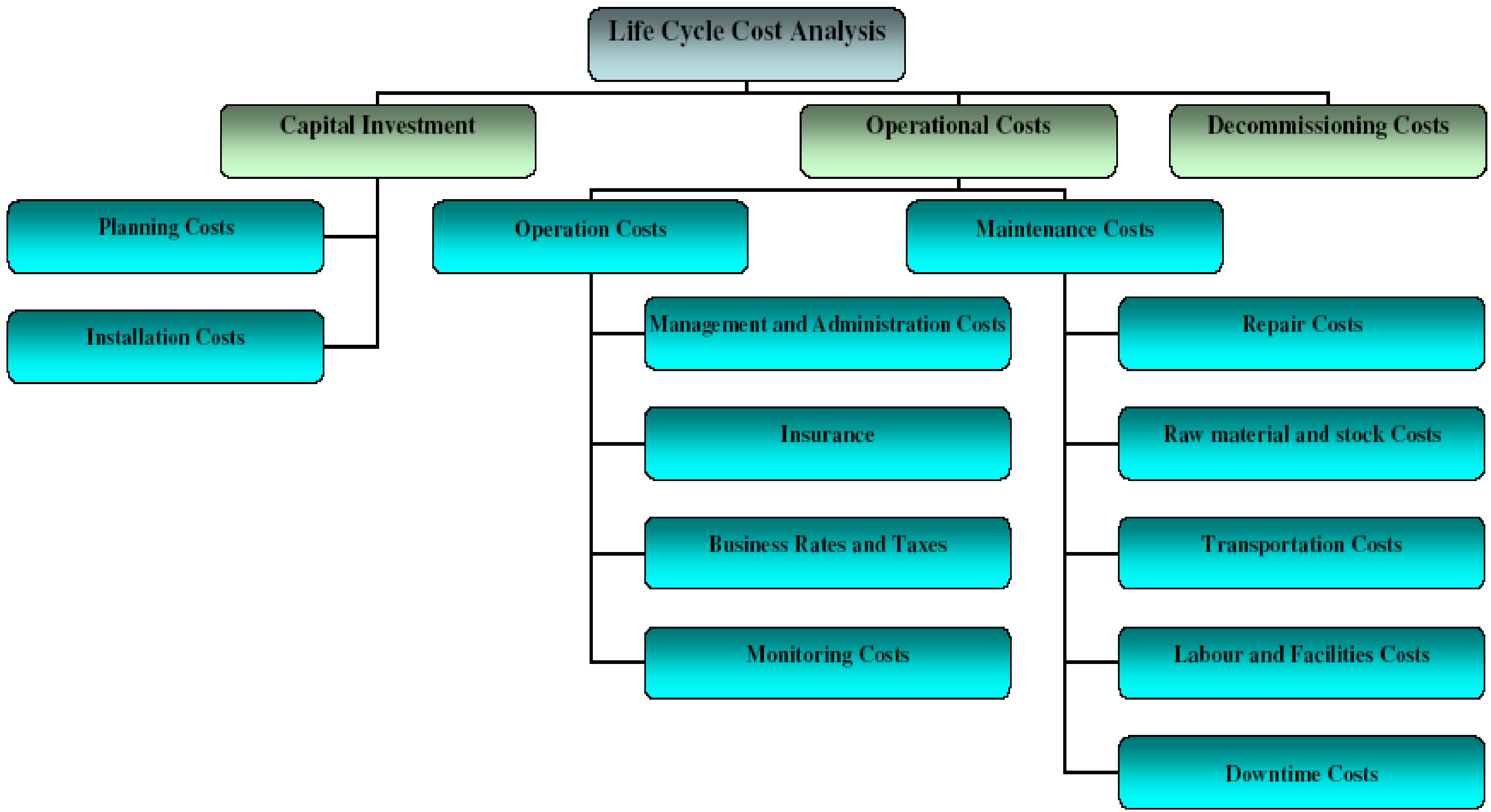

Figure 3.2 The Life Cycle Costs diagram for the Operation and Maintenance strategy of offshore wind farms

3.7 Structured Analysis and Design Technique

The Structured Analysis and Design Technique (SADT) is a tool that can be used to help construct algorithms for computer based simulation programs representing large and complex systems. It has been widely used by software engineers for software design, where complex relationships exist, such as it has been implemented in the US Air Force Integrated Computer Aided Manufacturing program.[75,76] The SADT analyses a real life system being represented in computer based simulation from a 'top-down' perspective, decomposing it systematically into subsystems, creating a hierarchical parent-child structure.[76] Graphical representations such as the 'actigram' shown in Figure 3.3, are used to represent the real life system and how it should be transformed into computer based simulations. There are five elements in the SADT graphical model as shown in Figure 3.3:[77]

- The **activity box** represents the different real life system tasks.
- The **inputs** to the activity box are the variables which will ultimately affect the outputs.
- The **outputs** are a function of the inputs having been affected by the activity box.
- The arrows flowing into the top part of the box represent **constraints or controls** of the activities and
- The final element represented by arrows flowing into the bottom of the activity box represents the **mechanisms** that carry out the activity.

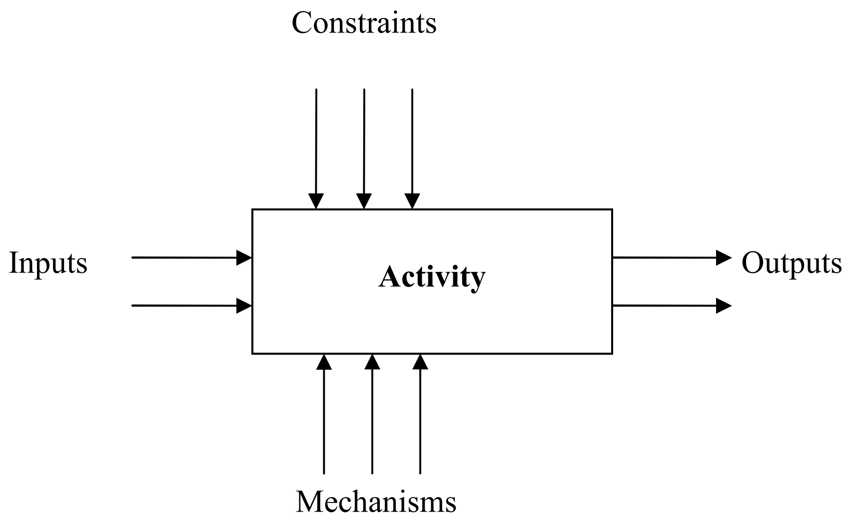

Figure 3.3 Graphical representation (Actigram) of a SADT diagram[75,78]

The SADT technique has been used to create a graphical representation of the operation of an offshore wind farm, as seen in Figure 3.4. This graphical representation will form the basis for developing computer based tools to simulate the planned intervention maintenance policy for offshore wind farms, as presented in the next Chapter. All the inputs, constraints, mechanisms and outputs of the operation of an offshore wind farm are explained in the following paragraphs.

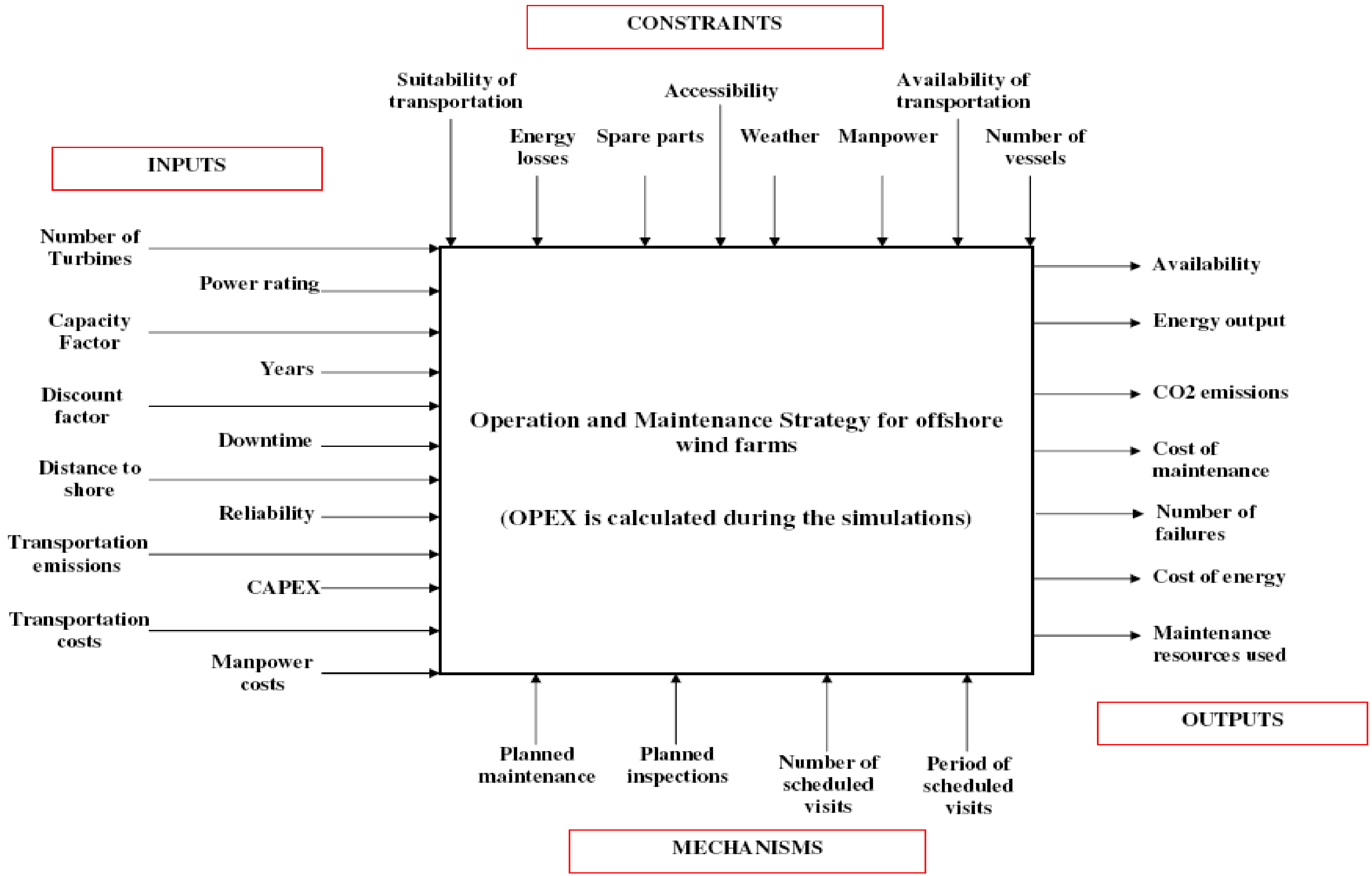

Figure 3.4 The Structured Analysis and Design Technique (SADT) diagram for the O&M activities of an offshore wind farm project [Diagram constructed based on 75, 76, 77 and 78]

Inputs are the necessary parameters for setting up the operation of an offshore wind farm. They are divided into fixed and variable input parameters. For instance the number of turbines and the years of operation of an offshore wind farm are fixed parameter and the reliability of wind turbines and downtime are variable parameters.

Number of Turbines. This is the number of wind turbines in the offshore wind farm.

Power Rating. This is the power rating of the offshore wind turbines. It is assumed all turbines have the same power rating.

Capacity Factor. The capacity factor is defined as the wind turbines' actual energy output for time t, divided by the theoretical maximum energy output if the machine operated at its maximum rated power for time t. A typical range of values for offshore wind farms is between 30-45%.

Years. This is the number of years that the offshore wind farm will operate. Typically 20 years.

Discount Factor. This is the discount factor for the calculation of the present value of money. Typically 5% is used.

Downtime. Downtime relates to the time needed for repairing each offshore wind turbine item and the time allocated for planned inspections. During the downtime the offshore wind turbine is non-operational, resulting in energy output losses.

Distance to shore. This is the distance of the offshore wind farm from the shore. Typically the distance from the nearest port facilities is used.

Reliability. This is the reliability of the offshore wind turbine. Each item of the wind turbine has its own failure rate levels.

Transportation emissions. This relates to the emissions of the vessels and helicopters used for the maintenance and repair of the offshore wind turbines. Typically they are measured in grams of CO2 emissions per km travelled.

CAPEX. This is the capital expenditure of the offshore wind farm. It is needed for the calculation of the price of unit of energy produced.

Transportation costs. This is the costs of the vessels or helicopters hired for the maintenance, repair or inspection of the offshore wind turbines. Typically daily rates are used.

Manpower costs. This is the costs of the personnel needed for the maintenance tasks and inspections of the offshore wind turbines. The number of the personnel and the working hours per day should be accounted for. Typically daily rates are used for 10 working hours per day.

Constraints are the factors that affect the O&M strategy of offshore wind farms and have an effect on the outputs of the project.

Suitability of transportation. Different maintenance transportation is used for the maintenance or repair of different wind turbine items. For instance for gearbox failures vessels are used due to the weight and complexity of the item. For planned inspections only helicopters are used.

Energy losses. The energy losses due to the downtime between the scheduled maintenance visits. When an offshore wind turbine fails between the scheduled visits it will remain non-operational until the next planned maintenance visit, which results in loss of energy. The energy loss can vary depending on the mechanisms of the planned intervention maintenance strategy i.e. period and number of scheduled maintenance visits.

Spare parts. This is the lead time for the spare parts for the repair of the offshore wind turbine components.

Accessibility. This is the accessibility levels to the offshore wind farm, which depend upon the weather state and the availability of transportation means.

Weather and sea state. The weather conditions and sea state at the specific location of the offshore wind farm affects its accessibility and availability levels.

Manpower. This is the availability of the personnel needed for the repair and inspection of the offshore wind turbines. It is a common practice for operators to hire higher number of personnel during high maintenance seasons.

Availability of transportation. This is the availability of vessels and helicopters and affects the maintenance expeditions for repair and inspections of the offshore wind turbines.

Number of vessels. This is the number of vessels or helicopters used for the maintenance of the offshore wind turbines and affects the cost of maintenance and the total CO2 emissions.

Mechanisms are the different aspects of a maintenance strategy for offshore wind farms. They form the factors that affect the way the O&M strategy can be implemented. Different outputs can result by changing these factors.

Planned maintenance. This is the selected maintenance strategy for the offshore wind farms, the planned intervention maintenance strategy.

Planned inspections. This is the scheduled inspections and preventive maintenance visits to the offshore wind turbines, for instance, oil change for gearboxes.

Number of scheduled visits. This is the number of planned maintenance periods per operational year for the planned intervention maintenance strategy. This is affected by the reliability levels of the offshore wind turbines and the cost of energy output.

Period of scheduled visits. This is the specific time at the operational year of the offshore wind farm that the planned maintenance visits will take place. Typically distinguished by the selection of a specific month. This is affected by the weather and sea state.

Outputs are the important results of the operation of an offshore wind farm. They are the factors to decide upon the economic viability of the offshore wind farm and the suitability of the selected O&M strategy.

Availability. This is the total availability of the offshore wind farm for 20 years of operation.

Energy output. This is the total energy output of the offshore wind farm minus the energy losses due to downtime.

CO_2 emissions. This is the total CO_2 emissions of the vessels and helicopters used for the maintenance of the offshore wind turbines.

Cost of maintenance. This is the total cost for the maintenance of offshore wind turbines for 20 years of operation.

Number of failures. This is the total number of failures of the offshore wind turbines.

Cost of energy. This is the cost of the energy produced, typically in pounds per kWh produced.

Maintenance resources used. This is the number of maintenance vessels and helicopters and the number of manpower used for the maintenance of offshore wind farm.

3.8 Conclusions

In this chapter the planned intervention maintenance policy has been described as a possible solution to the technical challenge of maintenance of offshore wind turbines. The differences between the existing practice of using the corrective maintenance strategy and the proposed solution of using the planned intervention maintenance policy have been discussed.

Two different analysis techniques have been introduced in this chapter, the LCCA and SADT that may be used to identify the key variables and different parameters that affect the application of planned intervention maintenance policy to offshore wind farms. The applicability of any given maintenance strategy will heavily depend on the effects these parameters have on the economic viability of offshore wind farms.

The conclusions reached from the development of the LCCA and SADT techniques for offshore wind farms will form the basis upon which a set of algorithms will be developed to simulate the operation of an offshore wind farm employing the planned intervention maintenance policy, as described in subsequent chapters.

4 Methodology and Algorithm Development

4.1 Introduction

This chapter gives the development of four models namely; the reliability, the economic, the energy and the Monte Carlo models, which fulfil the requirements of the identified lack of any available models for the planned intervention maintenance policy, as explained in Chapter 2. The development of these models is based on the conclusions and findings reached in Chapter 3 on the different parameters that affect an offshore wind farm. A set of computer simulation programs have been developed in this Chapter to simulate a planned intervention maintenance policy for offshore wind farms by implementing the four developed models and simulating the way they interact. The different steps of each of the computer simulation program are explained in detail in this Chapter, with the aid of Algorithm Boxes. These Algorithm Boxes give a representation of the algorithm developed for each of the computer programs that simulate the different models.

4.2 O&M strategy model development

When considering the conclusions reached from the critical review of available literature on the parameters that affect the offshore wind farm O&M strategy, as presented in Chapter 2, then Figure 4.1 represents the identified requirement for the development of an O&M model for simulating the maintenance practices of a planned intervention maintenance policy for offshore wind farms. Furthermore, the critical review in Chapter 2 also identified the requirement for the development of exclusive energy, reliability and economic models for the planned intervention maintenance policy, since the existing models are either incomplete or not applicable to the proposed maintenance strategy.

Now considering the activity box of Figure 3.4 in Chapter 3 (p. 86) which is a graphical representation of the planned intervention maintenance policy, then the different inputs, constraints and mechanisms of this activity box represent the different parameters of the energy, the reliability, the economic and Monte Carlo models that have to be developed. Figure 4.1 represents the relationship between these models, while each of these models take into consideration different parameters of the activity box of Figure 3.4 in Chapter 3 (p. 86). The development of these models is discussed further in this chapter and the different inputs, constraints and mechanisms of the activity box of Figure 3.4 that each model considers are explained. The reliability model, the economic model and the energy model have a bi-directional relation with the Monte Carlo model, which all together form the O&M model for the planned intervention maintenance policy.

1. The purpose of the reliability model is to calculate the reliability levels of offshore wind turbines, by considering the effect of the marine environment, as previously identified in Chapter 2.

2. The purpose of the economic model is to calculate the cost of wind energy produced and the total cost of maintenance over a 20 year period.

3. The purpose of the energy model is to calculate the total energy produced by the offshore wind farm by taking into consideration energy losses due to failures, repairs and downtime.

4. The purpose of the Monte Carlo model is to give the variability and stochastic behaviour of input parameters as identified in Chapter 2, using variables e.g. time to failure of wind turbines and fixed inputs e.g. number of wind turbines, which are collected from the other models and the simulations undertaken to produce the statistical results, e.g. likely wind farm availability.

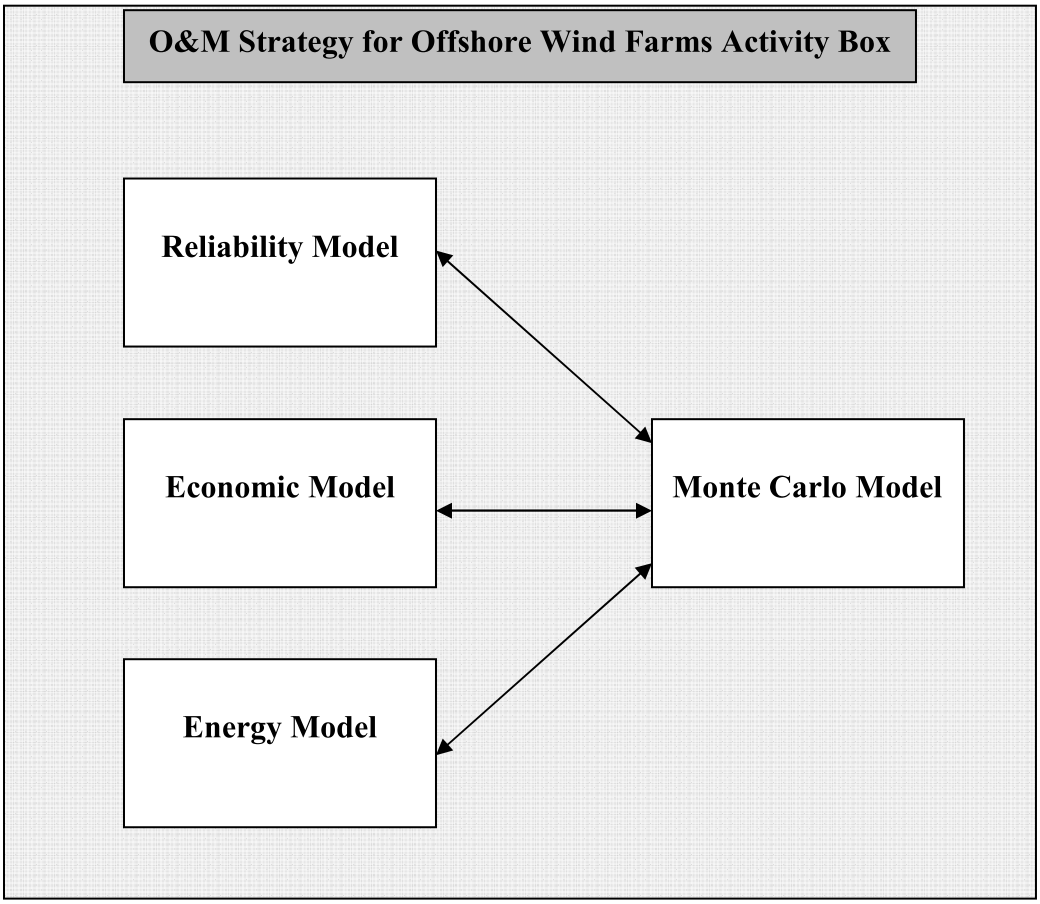

Figure 4.1 The four sub-blocks of the planned intervention maintenance policy activity box in Figure 3.4 (p. 86).

4.2.1 Reliability Model

Differences between onshore and offshore wind farms are summarised in Appendices D.1 and D.2, which shows that the offshore wind turbines are subject to higher stresses, both environmental and power utilisation, due to their location in the marine environment. Higher stressed operation often results in higher failure rates in offshore wind turbines, as compared to onshore wind turbines, this being previously explained in Chapter 2 and also in Appendix D.

Published data on the reliability levels of offshore wind farms does not exist, therefore in order to construct the reliability model it was necessary to use published data on the failure rates of onshore wind turbines to calculate the failure rate of offshore wind turbines. This has been achieved by considering that onshore and offshore wind turbines are of similar type and by taking into account the higher environmental and power utilisation stresses that they endure.

4.2.1.1 Review of onshore wind turbine failure rates

The failure rates of more than 9,500 onshore wind turbines were considered by examining the databases shown in Table 4.1, which covered three different European countries namely; Denmark, Germany and Sweden. More detail on these databases are given in Appendix E.[50,79,80,81,82,83,84]

Table 4.1 The onshore wind turbine failure rate databases considered, listed in order of related country.[50,79,80,81, 82,83,84]

Country	Databases used
Germany	WindStats; WMEP; LWK
Denmark	WindStats
Sweden	Felanalys; DV

A summary of the onshore wind turbine failure rates obtained from the databases for each country is presented in Figure 4.2. Onshore wind turbines in Germany are currently experiencing higher failure rates than wind turbines in Sweden and Denmark. From Figure 4.2 the average failure rate of onshore wind turbines across all three countries is 1.16 failures per year. The number of wind turbines in Sweden, however, is significantly less than Germany and Denmark, with the average of those two countries being somewhat greater at 1.54 failures per year.

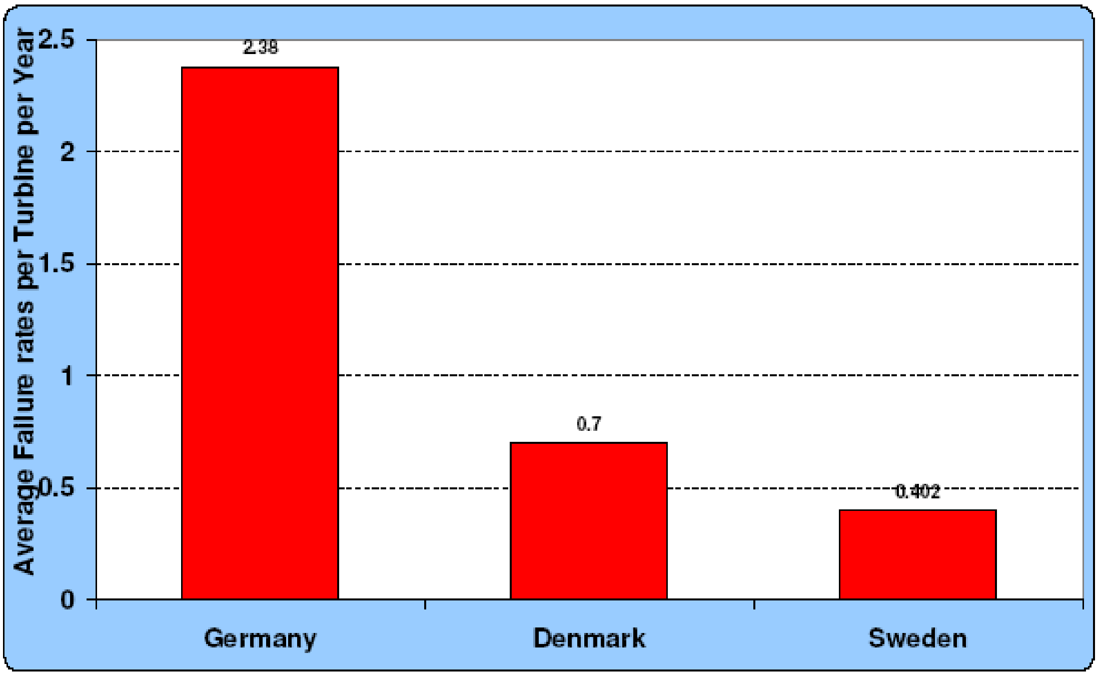

Figure 4.2 A summary of the average failure rates per wind turbine per year. A comparison between Germany, Denmark and Sweden.

The differences in failure rates between Germany and Denmark necessitated some deeper investigation. The "Wissenschaftlichen Mess- und Evaluierungsprogramm" (WMEP) database, which gives annual reports for 250 MW of onshore wind turbines located in Germany, was therefore analysed for years 2002 to 2006.[79]

The failure rates of different wind turbine components have been plotted in Figure 4.3, using information provided from three different databases. It can be seen that in general similar failure rates are recorded for each wind turbine component. However the Windstats database shows similar relative failure rates but lower in magnitude, the reason being the way the data are collected from wind turbine failure logging results in a very high percentage for the 'other' category. Clearly, the items that suffer the highest failure rates are the electrical systems and the power control units, as indicated by Arrows A and B in Figure 4.3. Each one of these contributes between 18 to 25% of the total failures of a wind turbine. Further details of the analysis of the WMEP database are shown in Appendix E.

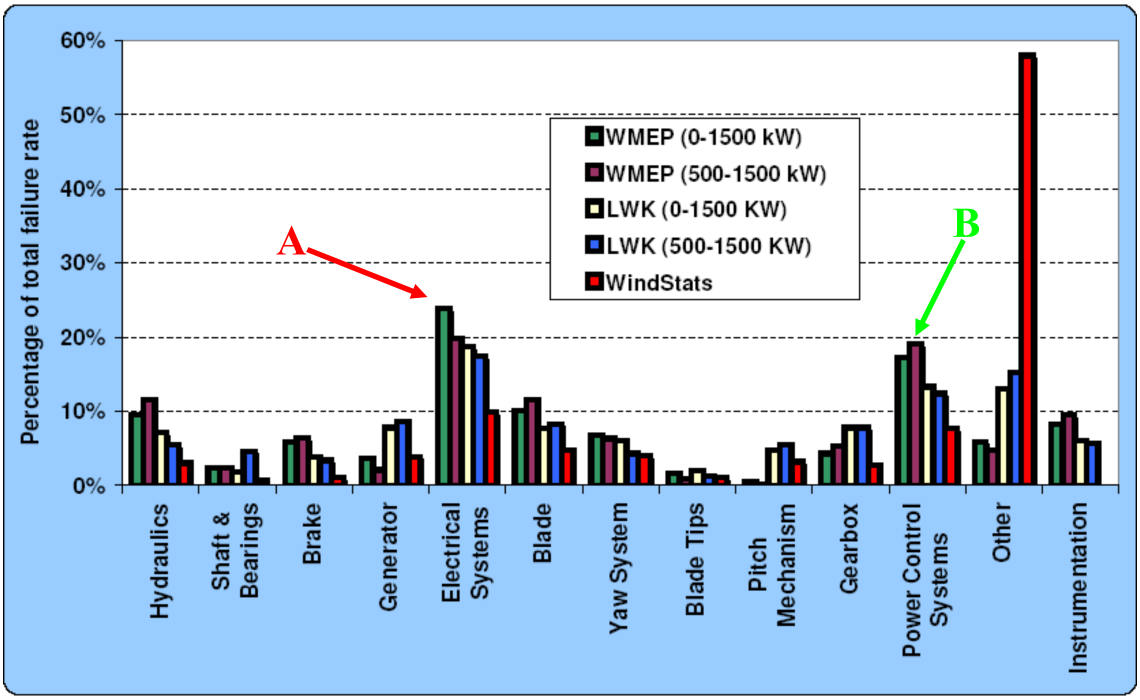

Figure 4.3 Summary of onshore wind turbine component failure rates as percentage of total from all the databases for Germany. Different wind turbine power rating ranges are presented for each database to distinguish large and smaller onshore wind turbines.[50,79,80,81,82,83,84]

Whilst the failure rates of onshore wind turbines could be used to define the boundaries of failure rates of offshore wind turbines they would ignore the increase in stress factors (environmental and power utilisation), which must be taken into consideration.

4.2.1.2 Onshore to offshore wind turbine failure rate transformation

To calculate the failure rates of stressed items when having knowledge of stress-free failure rates, then the equation below can be used:[85]

$$\lambda_{XA} = \lambda_{O}\left(K_1 \times K_2 \times \cdots K_n\right) \times p(A) \tag{4.1}$$

Where:

λ_{XA} is the predicted failure rate for a system, for failure mode A. Considering a wind turbine, then λ_{XA} is the calculated offshore wind turbine failure rate.

λ_O is the base failure rate of the system, in ideal conditions of minimal stress levels.

K_1, K_2, K_n are the stress factors (environmental, power utilisation, etc.) for different conditions that the system is used in.

p(A) is the proportion of failure rate for every failure mode of the system. By adding the proportions of failure rate for all the failure modes of the system then p(A) becomes unity.

To calculate the failure rates of offshore wind turbines, when having knowledge of onshore wind turbine failure rates, then equation 4.1 can be modified as follows:

$$\lambda_{Offshore} = \lambda_{Onshore} * \left(K_{1(Offshore)} * K_{2(Offshore)}\right) * p(A) \tag{4.2}$$

Where:

K_1 is the environmental stress factor and is defined as the effect that exogenous conditions have on the reliability of an offshore wind turbine, i.e. the effect of the weather and the marine environment.

K_2 is the power rating stress factor and is defined as the effect that different operating power ranges of the wind turbine will have on its reliability. The percentage utilisation of offshore wind turbines is higher compared to equivalent onshore wind turbines due to the higher winds experienced offshore.

4.2.1.3 Implementation of K_1 and K_2 stress factors

Considering offshore wind farms there are no accepted values that can be applied to specify K_1 and K_2 stress factors. Tables 4.2 and 4.3 show published empirical data that can be used for the purposes of offshore wind farms.

Table 4.2 shows the different environmental conditions and the environmental stress factors applied. By setting the general environmental conditions for onshore wind turbines as ‘general purpose and ground based’ i.e. $\mathbf{K_{1\ onshore} = 1}$, then the environmental stress factor for offshore wind turbines should be in the range between ‘Marine sheltered’ and ‘Marine exposed’, i.e. $\mathbf{1.5 < K_{1\ offshore} < 2}$.

The ‘Marine sheltered’ definition relates to items that are located in the marine environment but not exposed, whilst ‘Marine exposed’ is used for items that are fully exposed to the marine environment. The analogy for an offshore wind turbine is that the ‘Marine sheltered’ items of the wind turbine are those items within the nacelle e.g. the gearbox, generator, drive train etc, whilst the ‘Marine exposed’ items are represented by the blades, blade tips, antennas, wind vanes, tower and other items on the nacelle and the outer plane of the nacelle housing. These definitions being extracted from Table 4.2.[85]

Table 4.2 Environmental stress factors. The values are based on empirical data retrieved from ref. 85

General Environmental Conditions	Environmental stress factor K_1
Ideal, static conditions	0,1
Vibration free, controlled environment	0,5
General-purpose, ground-based	1
Marine, sheltered	1,5
Marine, exposed	2
Road	3
Rail	4
Air	10
Missile	100

Now consider the power rating stress factor K_2. The key parameter to be considered is the windiness of the wind farm site. The windiness of a wind farm is measured by the capacity factor. Table 4.3 shows the percentage of component nominal power rating and the related power rating stress factors. Table 4.3 has been replicated in Figure 4.4, which shows the exponential increase in stress factors that occurs as component ratings are increased beyond their nominal ratings.

Table 4.3 Power rating stress factors for mechanical components. The values are based on empirical data retrieved from ref. 85

Percentage of component nominal rating	Power rating stress factor K_2
140	4
120	2
100	1
80	0,6
60	0,3
40	0,2
20	0,1

The capacity factor for a wind farm located onshore can range between 18% and 28%,[7,8,9,32] but for existing offshore wind farms, located near-shore, the capacity factor has a calculated average value of 34.2%, as derived in Appendix D.1 and D.2. It is anticipated that future offshore wind farms located further offshore will have capacity factors of up to 45%.[7,8,9,32] (See also Appendix D.)

Accepting 25% as being the average onshore wind farm capacity factor,[7,32,35] which is represented as 100% of component nominal rating, then from Figure 4.4, $\mathbf{K_{2\ Onshore} = 1}$ as indicated by Arrow A. Now assuming the equivalent offshore wind farm capacity factor varies between 34.2% and 45% for near and far offshore wind farms respectively then $K_{2\ Offshore}$ will range between 1.447 (Arrow B) and 2 (Arrow C), as obtained from the curve seen in Figure 4.4 ($\mathbf{1.447 < K_{2\ Offshore} < 2}$).

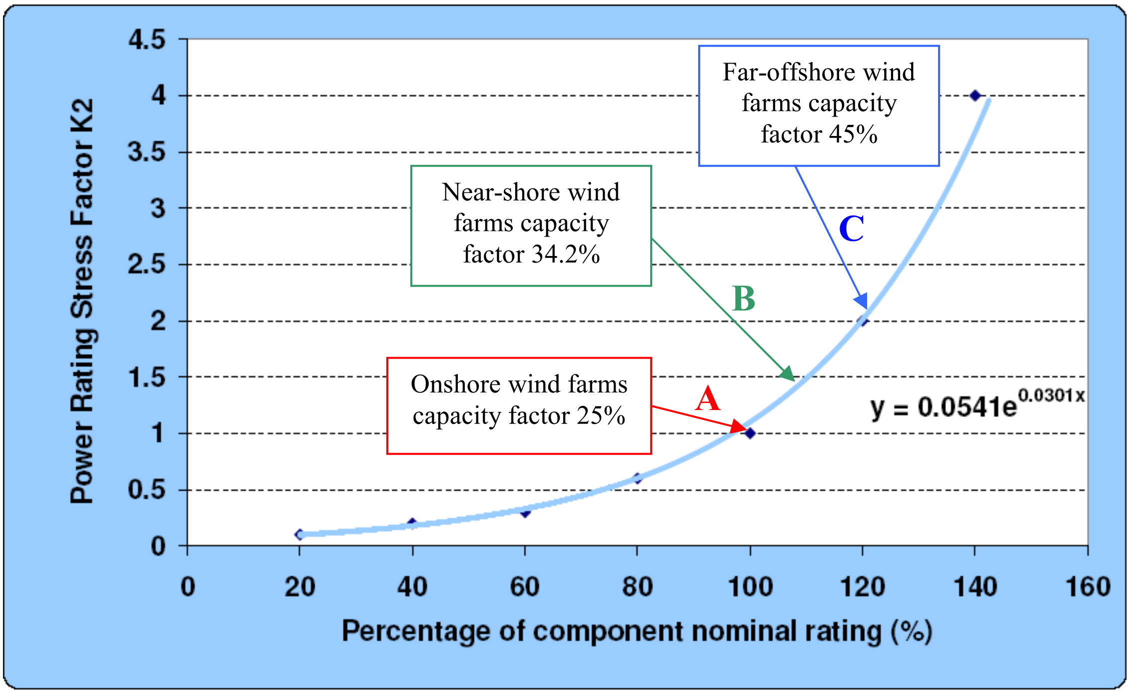

Figure 4.4 Percentage of component nominal rating plotted against stress factor K_2. Graph constructed based on the data presented in Table 4.3.

4.2.1.4 Development of equations for the reliability model

Applying the boundary values for K_2 and making p(A) equal unity, thereby accounting for all the failure modes of the wind turbine, equation 4.2 can be expressed in terms of near-shore and far-offshore wind turbine failure rates as follows:

$$\lambda_{Near-shore} = \lambda_{Onshore} * K_{1(Offshore)} * 1.447 \tag{4.3}$$

$$\lambda_{Far-Offshore} = \lambda_{Onshore} * K_{1(Offshore)} * 2 \tag{4.4}$$

Where, K_1 ranges between 1.5 and 2, as analysed earlier in this paragraph.

Using equation 4.3 to construct Figure 4.5 it is possible to see the range of near-shore wind turbine failure rates as a function of onshore wind turbine failure rates, presented by the shaded area on the graph. The x-axis range has been previously determined from the analysis of onshore wind turbine failure rates as being between 1.16 and 1.54 failures per year, whilst the two different lines represent the boundary values calculated for the K_1 stress factor, i.e. 1.5 and 2. The range of near-shore wind turbine failure rates can now be read from the y-axis.

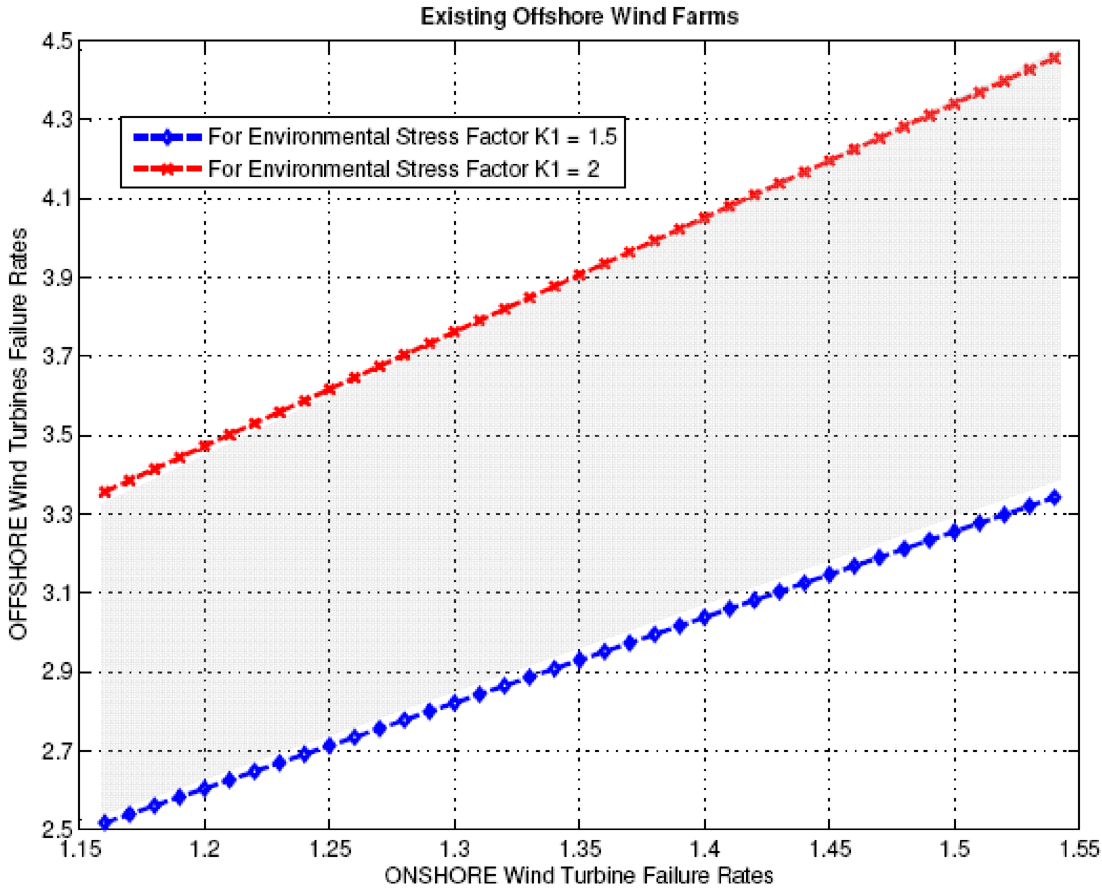

Figure 4.5 Calculated failure rates for the near-shore wind turbines based on equation 4.3, where K_2=1.447, and for K_1=1.5 then $2.5 \leq \lambda_{Near\text{-}shore} \leq 3.15$, and for K_1=2 then $3.35 \leq \lambda_{Near\text{-}shore} \leq 4.45$

Similarly Figure 4.6 is constructed using equation 4.4 to determine the range of failure rates for far-offshore wind turbines. Again the two lines present the boundary values of the K_1 stress factor from which the range of far-offshore wind turbine failure rates can be read.

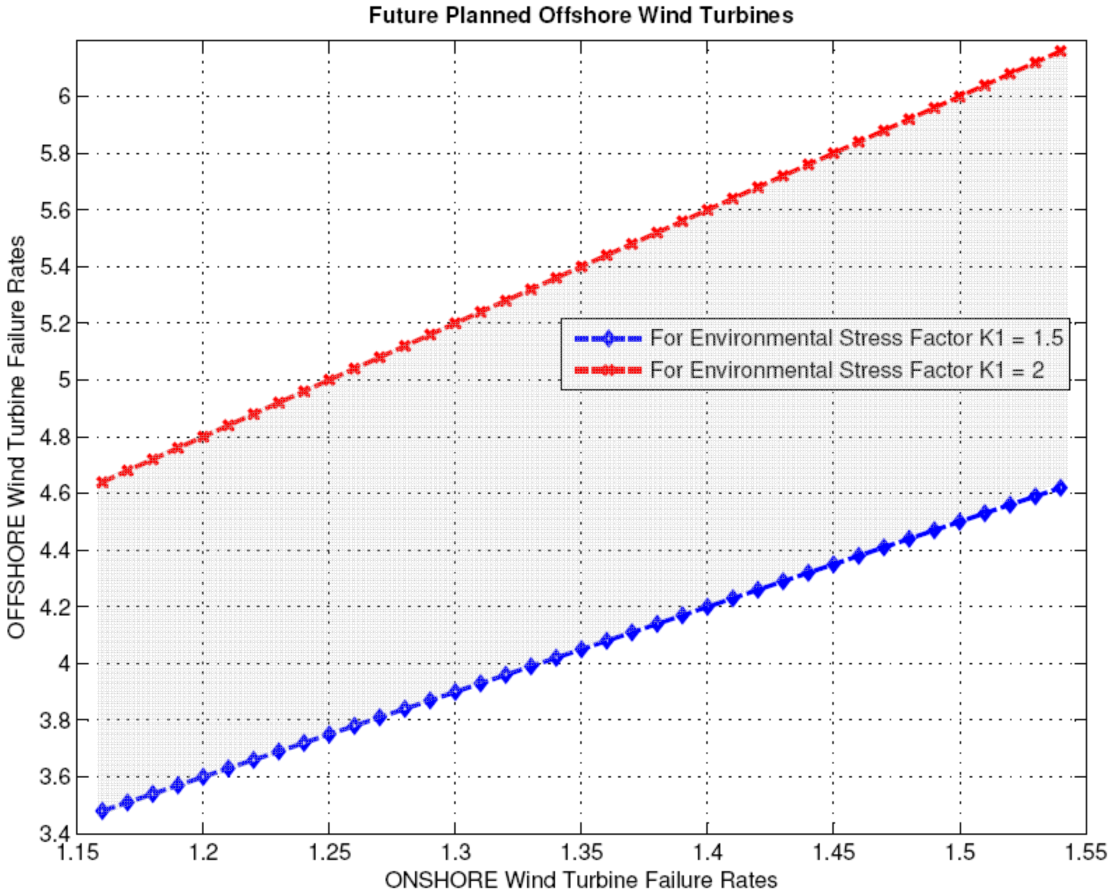

Figure 4.6 Calculated failure rates for the far-offshore wind turbines based on equation 4.4, where $K_2=2$, and for $K_1 = 1.5$ then $3.5 \leq \lambda_{Far\text{-}Offshore} \leq 4.41$, and for $K_1 = 2$ then $4.62 \leq \lambda_{Far\text{-}Offshore} \leq 6.18$

The reliability model has therefore used onshore wind turbine failure rate data with appropriate stress factors to determine offshore wind turbine failure rates to overcome the lack of hard data available from the industry.

4.2.2 The Economic Model

To calculate the cost of energy produced by offshore wind farms the use of a standard discounting calculation, the Levelised Production Cost (LPC) technique, has been adopted. The justification being that this technique is the main method proposed by the IEA (International Energy Association)[74] to compare the competitiveness of a wind farm project, while other studies reporting on wind farm cost calculations have also used this technique.[26,31,4]

The LPC is '*the cost price of production per unit of energy, which is expressed in actualised nominal money*'.[71] In other words the LPC expresses the production cost of energy in terms of current purchasing power. The general equation to calculate the LPC is given below:[71]

$$LPC = \frac{\sum_{t=0}^{T_{EC}} C_{tot} \cdot (1+r)^{-t}}{\sum_{t=0}^{T_{EC}} (E_{tot} - E_{Loss})} \tag{4.5}$$

Where:

C_{tot} is the total expenditures for year t,

E_{tot} is the total energy production for year t,

E_{Loss} is the energy lost due to downtime, maintenance activities,

T_{EC} is the economic lifetime of the project and

r is the interest rate.

By applying the conclusions and observations made from the LCC Analysis presented in the previous chapter, i.e. taking into consideration the costs associated with the construction and operation of an offshore wind farm, the LPC in equation 4.5 becomes:

$$LPC = \frac{I_{tic} + \left\{ \sum_{t=0}^{T_{EC}} \frac{C_{O\&M} + C_S + C_R}{(1+r)^t} + C_{DEC}(1+r)^{-t} \right\}}{\sum_{t=0}^{T_{EC}} (E_{tot} - E_{Loss})} \tag{4.6}$$

Where:

I_{tic} is the total investment cost of the offshore project (CAPEX), usually incurred in year zero.

$C_{O\&M}$ is operations and maintenance costs, which incur each year.

C_S unpredictable costs e.g. unexpected environmental damage.[26]

C_R is the component costs associated with $C_{O\&M}$.

C_{DEC} is the decommissioning costs, which are the cost associated with dismantling the offshore wind farm and are incurred in the year after the last year of operation, i.e. year 21.

The unpredictable costs C_s can be assumed to be zero since there is no easy way to calculate them. C_R costs are absorbed into the capital investment cost I_{tic}, i.e. initial spares costs, and also into maintenance costs $C_{O\&M}$ for ongoing spare costs. Decommissioning costs, which must be estimated because no offshore wind farm has yet been decommissioned, can be determined as a percentage of capital investment costs, the percentage value being 2.5% of the capital investment cost, which is incurred in the year after the last of the project, i.e. year 21.[70,71,72,73] For simplicity the decommissioning costs can be added to the capital investment cost, so equation 4.6 can be rewritten as follows:

$$LPC = \frac{I_{total} + \left\{ \sum_{t=0}^{T_{EC}} \frac{C_{O\&M}}{(1+r)^t} \right\}}{\sum_{t=0}^{T_{EC}} \left(E_{tot} - E_{Loss} \right)} \tag{4.7}$$

Where I_{total} is the I_{tic} and the C_{DEC} added together.

Considering the analysis of O&M strategies in Chapter 3, then $C_{O\&M}$ can be broken down into three sub-costs namely labour costs, repair costs and transportation costs, therefore equation 4.7 becomes:

$$LPC = \frac{I_{total} + \left\{ \sum_{t=0}^{T_{EC}} \frac{C_{labour} + C_{transportation} + C_{repairs}}{(1+r)^t} \right\}}{\sum_{t=0}^{T_{EC}} \left(E_{tot} - E_{Loss} \right)} \tag{4.8}$$

Where:

C_{lobour} are the costs associated with the daily rates for technicians and other maintenance personnel,

$C_{repairs}$ are the cost associated with the repair of the faulty items of the offshore wind turbines, including all the necessary materials and consumables i.e. gearbox oil changes and tools used.

$C_{transportation}$ are the cost associated with hiring appropriate transport means, e.g. ships and helicopters, for the transportation of items and personnel to the offshore wind farm.

Algorithm Box 1: Calculation of the cost of maintenance expeditions

```
% Calculation of the maintenance costs for components that need
  helicopter transportation:

C_om1(find(ttf<=0)) = MTTF_Heli * (( ttr(find(ttf<=0)) * 365 *
                      (C_PM_labour + C_PM_Heli) ) + (
                      tpm(find(ttf<=0)) * 365 * (C_PM_labour +
                      C_PM_Heli) ) - C_PM_material);

% Calculation of the maintenance costs for components that need
  vessel transportation:

 C_om2(find(ttf<=0)) = MTTF_Vessel * (( ttr(find(ttf<=0)) * 365 *
                       (C_CM_labour + C_CM_Vessel) ) + (
                       tpm(find(ttf<=0)) * 365 * (C_PM_labour +
                       C_PM_Heli) ) - C_CM_material);

% Calculation of the total maintenance costs for this period:

C_om(find(ttf<=0)) = C_om1(find(ttf<=0)) + C_om2(find(ttf<=0));

% Comment: The black colour represents the actual algorithm and the
  green colour represents comments.
```

Algorithm Box 1 gives an example of how the costs of maintenance expeditions are calculated in the core O&M program using the economic model. For each maintenance period the model searches which offshore wind turbine has failed, i.e. '(find(ttf<=0))', by testing the time to failure (ttf) of each wind turbine. Then the maintenance costs are divided into two subsections 'C_om1' and 'C_om2' as different items require different transportation method, helicopters and vessels respectively. Then for each identified failed item the associated time for repair (ttr) and time for inspection (tpm) are used for the calculation of the costs of the maintenance expeditions. The cost of maintenance personnel 'C_PM_labour' and the cost of hiring a vessel or helicopter 'C_PM_Heli' or 'C_CM_Vessel' are also considered depending on the item that has failed. The cost for repairing the failed items 'C_PM_material' and 'C_CM_material' by helicopters or vessel respectively, are calculated based the economical information provided by a number of studies reporting on wind turbine item costing,[45,39,61,62,86,87,108] (see examples in Appendix B.5). The total maintenance costs for the repair of all the failed components 'C_om' are calculated for every maintenance period and every operational year.

4.2.3 Energy Model

The energy model calculates the total wind generated energy each offshore wind turbine produces, using the following equation:[41]

$$E_{out} = \sum \Delta E = \sum [[(P_{out}) * (t) * (CF)] - E_{Loss}] \qquad (4.9)$$

Where:

E_{out} is the total wind generated energy produced over time t.
P_{out} is the wind turbine power rating.
t is the time that the wind turbine is operating.
CF is the capacity factor of the wind farm.
E_{Loss} is the energy loss due to the wind turbine being inoperable.

The maximum energy that can be produced over period t depends upon the capacity factor, which in turn depends upon the windiness of the site, and the power rating of the wind turbine. Further details of the power output of wind turbines are presented in Appendix A. The energy model uses the averaged monthly wind energy for a given location to determine the total monthly energy output. Figure 4.7 shows the typical monthly variation in average wind energy in the UK, expressed as a percentage of total annual energy. The actual energy produced over period t depends upon the availability of the wind farm, which in turn determines the energy loss due to downtime i.e. failures and repairs.

Wind resources vary significantly between locations so it is not realistic to use wind characteristics recorded at one offshore site and apply them to other sites.[64] The graphs and figures presented in Appendix C show the variations in wind speed and wave heights offshore UK, indicating seasonal patterns for winter and summer months. Clearly wind speed relates to capacity factor which will be different for different offshore wind farm sites, whilst sea states relates to the capability of accessing the wind turbines, i.e. restrictions on transferring personnel and equipment onto offshore wind turbines.

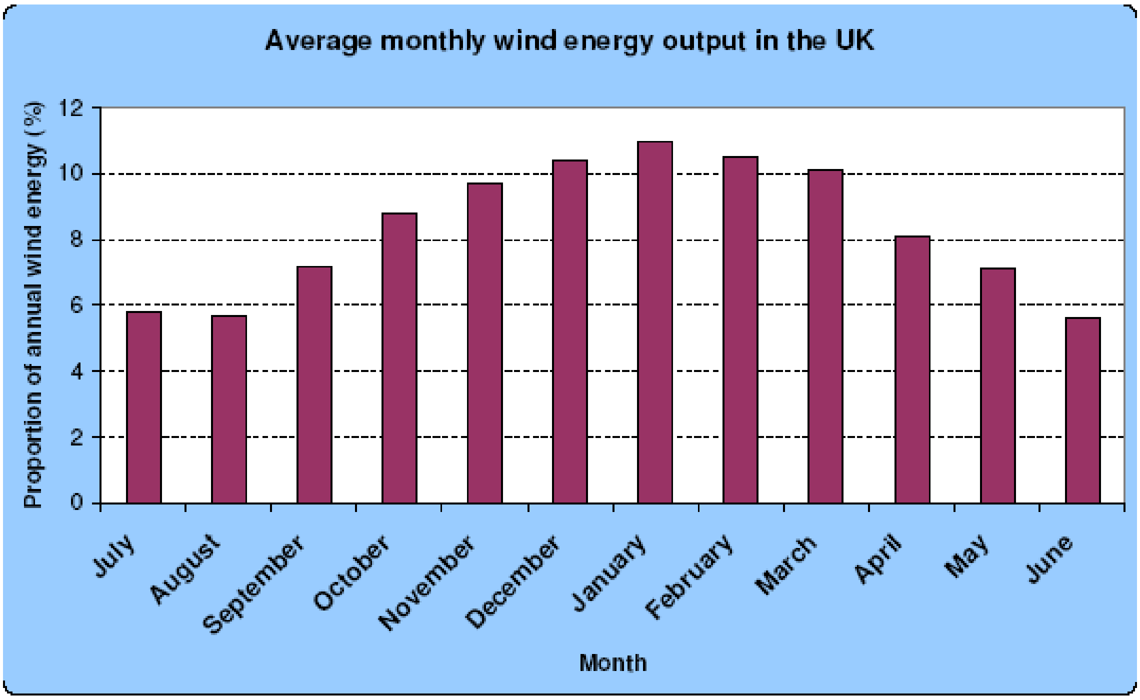

Figure 4.7 Variation in average monthly wind energy output for the UK (Graph generated using values obtained from ref. 64)

The energy model has been implemented in two parts namely the 'Power-Fit' algorithm and the core O&M model. Equation 4.9 is used to calculate the energy output based on Figure 4.7. Equation 4.9 is used by the core O&M program and Figure 4.7 by a program called 'Power-Fit' as shown in Algorithm Box 2.

Algorithm Box 2 shows the 'Power-Fit' algorithm which determines the energy output from knowing the time to failure of a wind turbine. The algorithm will interpolate the time to failure, which is passed on to 'Power-Fit' program from the O&M program, to find the exact time in a specific month (x-axis of Figure 4.7) failure occurs to determine the energy output. For example, for a planned intervention maintenance policy with one scheduled maintenance period per operational year, the ‘ttf’ (time to failure measured in years) reduces by one year for every scheduled annual maintenance period. Should ‘ttf’ become zero then the wind turbine has failed and should it fail between scheduled annual maintenance periods the ‘Power-Fit’ algorithm calculates how much energy the offshore wind turbine has produced up to the point in time it failed.

Algorithm Box 2: Interpolation between time to failure of a wind turbine and the energy output

```
% Values in table k: first column - time to failure (ttf) value,
                     second column - energy output:

                          k=[     0     100
                             -0.0833   94.4
                             -0.1666   87.3
                             -0.2499   79.2
                             -0.3332   69.1
                             -0.4165   58.6
                             -0.4998   47.6
                             -0.5831   37.2
                             -0.6664   27.5
                             -0.7497   18.7
                             -0.833    11.5
                              -0.9163   5.8
                              -1         0];

%Interpolation command:

power_out1 = interp1(k(:,1),k(:,2),ttf,'cubic');
```

When a wind turbine fails between the scheduled annual maintenance periods then it will remain non-operational meaning the potential to generate energy is lost until maintenance and repairs are carried out. Algorithm Box 3 gives an example of how the energy loss is calculated in the core O&M program for every wind turbine in an offshore wind farm that has failed between maintenance periods and then uses the calculated loss together with the maximum potential energy output to determine actual energy output. The actual energy output has therefore been calculated from knowing monthly average wind speeds and time to failure.

Algorithm Box 3: Calculation of energy output and energy losses in the core algorithm

```
% Interaction with 'Power-Fit' program to interpolate the ttf with
  energy output:

power_out2 = powerfit_season2_array(floor((multi_presic2) *
             ttf(find(ttf<=0))) + 1);

% Calculation of energy losses for planned inspections (ELoss):

power_loss(find(ttf<=0)) = (multi_month_selection_May) *
                           tpm(find(ttf<=0));

% Calculation of energy losses for repairs (ELoss):

repair_power_loss(find(ttf<=0)) = (multi_month_selection_May) *
                                  ttr(find(ttf<=0));

% Subtracting the energy losses from the energy output, i.e. using
  equation 4.9:

turbine_power(find(ttf<=0)) = ( (power_out2 / 100) +
                              power_loss(find(ttf<=0)) +
                              repair_power_loss(find(ttf<=0)) );
                              .
                              .
                              .
% Calculation of total energy output (Eout)

proj_power(j) = sum(annual_power) * capacity_factor *
                turbine_rating;
```

4.2.4 Monte Carlo Model

This paragraph explains how the Monte Carlo model is implemented to simulate the planned intervention maintenance policy for offshore wind farms. The justification for stochastic approach of the model is discussed and the advantages and disadvantages of the Monte Carlo method are explained.

4.2.4.1 Justification for stochastic approach

Modelling the planned intervention maintenance policy for an offshore wind farm is complex because the model requires an understanding of the interdependencies of a number of stochastic parameters including failure rates of wind turbines, wind and sea state variability, mean time to repair the wind turbines, and energy loss due to downtime.[10] A deterministic approach to modelling the planned intervention maintenance policy would therefore not produce sufficiently accurate results, because the model would have to be constrained to a fixed set of input values.[42,49]

On the other hand, to develop an analytical solution for modelling a system with statistical processes is often only possible for simple representations of the system.[88] These analytical solutions for a simple representation of the system are presented in Appendix F, where they show a mathematical representation of the first year of wind farm operation.

To overcome the variability of the key parameters of the O&M strategy an appropriate simulation method has to be implemented and a number of methods have been investigated, as discussed in Appendix G.4. The chosen method was Monte Carlo simulations, this being explained in the following paragraphs.

4.2.4.2 Introduction to Monte Carlo modelling

Monte Carlo simulations can be used for system reliability and availability modelling, using suitable computer simulation programs, since for the Monte Carlo simulations there are no constraints regarding the nature of input assumptions on parameters, e.g. variable failure and repair times of systems can be simulated.[89]

'*In a Monte Carlo simulation, a logical tree of the system being analysed is repeatedly evaluated, each run using different values of the distributed parameters. The selection of parameter values is made randomly, but with probabilities governed by the relevant distribution functions.*'[89]

For offshore wind farms, the use of the Monte Carlo simulation allows an understanding of the variable of input parameters, e.g. the time to failure and time for repairs, to statistically predict output performance for a given maintenance strategy e.g. planned intervention maintenance policy.

The main aim of using Monte Carlo simulation is to understand statistical variability of the failure rates and time to repair of offshore wind turbines using reliability data analysed in the reliability model previously presented and also in Appendix E. Every item of the wind turbine will have a failure rate, i.e. the inverse of time to failure, and a repair time at the beginning of its operation, i.e. at beginning of year one. Every time a item fails and is repaired a new failure rate is assigned to that item and hence to the offshore wind turbine. This process is performed for every failure at every maintenance period of the project, and is simulated over a large number of iterations needed for the Monte Carlo analysis, in order to obtain the statistical output performance variability of the availability of the wind farm, the cumulative energy output, the levelised production cost of energy and CO2 emissions.

Using the Monte Carlo method in this way requires extensive amount of computer resources to produce the statistical output performance results. Since every event of the offshore wind turbine, i.e. failure, repair, inspection, is sampled for every scheduled maintenance period of the operational year of the offshore wind farm, a simulation for all the wind turbines over 20 years of operation requires a large amount of computer processing time. This is multiplied many times as a consequence of the large number of iterations needed for the input parameters hence these techniques of Monte Carlo method increase substantially the computational time.[89]

On the other hand, the Monte Carlo method does allow a statistical observation of outputs using random inputs achieved by repeatedly assessing random simulations of the same input population to observe behaviour,[6] (see examples in Appendix G.1).

4.2.4.3 Monte Carlo Model implementation

The different steps followed for implementation of the Monte Carlo modelling were:

- To isolate key input variables of the statistical process for modelling,
- Associate a probability distribution for each input variable,
- Produce a large number of random values for these variables, in respect to the probability distribution equation,
- Store the output results of the model from each simulation, and
- Evaluate the outputs by statistical observation.

A mathematical representation of the sequence of steps described above has taken the following form:[88,90]

Let x_1, x_2,… x_n be a set of n independent random samples of the key variable. Then let $h(x_i)$, i = 1, 2,... n be the function of x. By considering the above, the estimation of the mean $\tilde{h}_n$ of the calculated value is presented in the following equation:[88,90]

$$\tilde{h}_n = \frac{1}{n}\sum_{i=1}^{n} h(x_i) \tag{4.10}$$

When considering the Monte Carlo simulation method applied to the maintenance strategy of offshore wind farms then the system which includes the maintenance process corresponds to the model, whilst the key input variables of the model correspond to the items of the system.[88] In that respect an appropriate way to model the system is a network of components which have different states (operational, failed or undergoing repair), as shown in Figure 4.8 below:

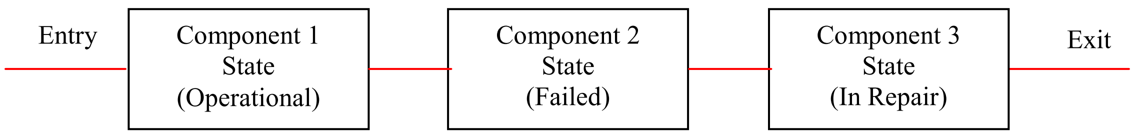

Figure 4.8 Representation of the Operation-Fail state of offshore wind turbines

Accepting that the major components of the wind turbine are in series and have no redundancy, as detailed in Appendix D.1 and D.2, then the wind turbine will be non-operational in the case of a major component failure. By considering Figure 4.8, every component that fails or is being repaired will cause the wind turbine to be non-operational, until the next planned intervention period or until the repair task is finished.

4.2.4.4 Development of equations for the Monte Carlo model

The time of failure of an offshore wind turbine component can not be precisely predicted, it can only be described by the stochastic methods.[5] Such ‘time to failure’ (ttf) values can be used to produce a probability distribution which can give the chance that a item has failed prior to a predefined time, t.[5] In that respect, the probability that a item fails prior to time t, is termed the item’s unreliability F(t). The corresponding probability density function f(t) of this unreliability is calculated by using the following equation:[5,91]

$$f(t) = \frac{dF(t)}{dt} \tag{4.11}$$

The measure of this unreliability of a system or a item is the failure or hazard rate, which if plotted against time then the resulting graph is called the 'bath-tub' curve as shown in Figure 4.9.

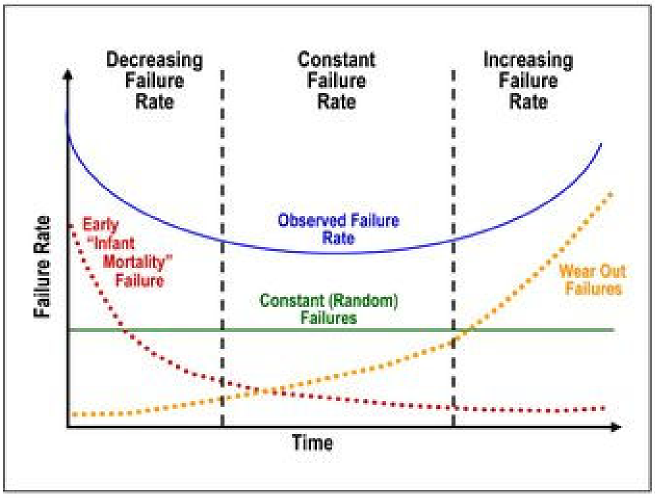

Figure 4.9 A typical bath-tub curve.[71] (This graph is only for reference to explain the theory behind it and its shape does not necessarily apply in this form to all the offshore wind farms that exist. This bathtub curve represents a very complicated scenario)

There are three characteristic areas on the graph in Figure 4.9. The first one is the infancy or burn-in period, where initial item or system failures show a decrease in the failure rate in the early stages.[5,91] The second period of the curve which shows a constant failure rate is termed the useful life period, where the failures are random.[5] Finally the last stage of the curve is the wear-out period, where an increasing failure rate will occur as the item or the system reaches its end of life.[5,91] The failure rate of a item or system will determine availability.

The inherent availability can be defined as '*The fraction of the total time that a device or system is able to perform its required function*',[5] and is calculated by equation 4.12 below: [5,91]

$$Availability = \frac{MTTF}{MTTF + MTTR} \tag{4.12}$$

Where MTTF is the mean time to failure and MTTR is the mean time to repair. The equation that represents MTTF is the reciprocal of the failure rate or:[5,91]

$$MTTF = \frac{1}{\lambda_f} \tag{4.13}$$

Furthermore, MTTR is the mean time to repair or in other words is the time taken between the failure of the item and its start-up as shown in Figure 4.10.

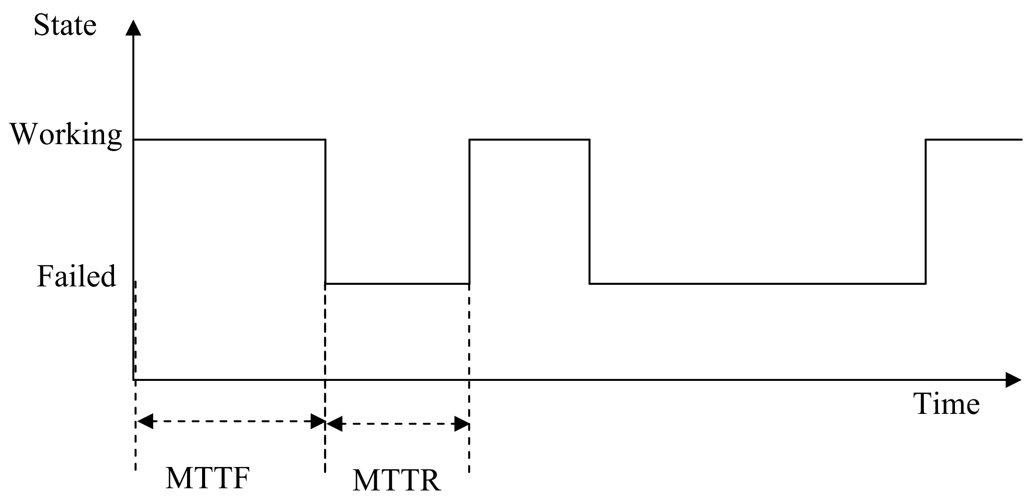

Figure 4.10 An example of a life history of a repairable item

By considering the equations 4.11 to 4.13, the inverse reliability equation used by the Monte Carlo simulation for the algorithm development is derived from the density function (equation 4.11) of the exponential distribution, as explained in [5]:

$$f(t) = \frac{1}{\mu} e^{-t/\mu} \tag{4.14}$$

If equation 4.14 represents the variability in 'time to failure' for offshore wind turbines with mean μ, then random numbers can be generated using this distribution expressed as the cumulative failure distribution:

$$F(t)=1-e^{-t/\mu} \tag{4.15}$$

The cumulative failure distribution has the same range and properties as the distribution of random numbers.[5] Hence, in order to generate random numbers X for the Monte Carlo simulations it is necessary to equate X with F(t) with values between zero and one:

$$X=1-e^{-t/\mu} \quad \text{or} \quad t=\mu\cdot\ln(1-X) \tag{4.16}$$

As the numbers represented by X are uniform over the range zero to one, then the same is true for '1-X', and equation 4.16 can be simplified as:

$$t=\mu\cdot\ln(X) \tag{4.17}$$

Therefore considering the Monte Carlo method, the failures of the wind turbines (ttf) along with the downtime, the repair times (ttr) and the time for inspection (tpm) of the items of each wind turbine are generated stochastically, according to the above equations, as shown in Algorithm Box 4.

Algorithm Box 4: Implementation of equation 4.17 in the Monte Carlo model

```
%---------------Generation of random variables--------------------%

X = rand(turbines,1);

ttf = -mttf * (log(X));

%---------Calculation of ttr and tpm when ttf <= 0 ---------------%

ttr(find(ttf<=0)) = mttr * log(rand(length(find(ttf<=0)),1));

tpm(find(ttf<=0)) = mtpm * log(rand(length(find(ttf<=0)),1));

% When ttf <= 0, then the wind turbine has failed
```

The random numbers 'X' are generated for every 'ttf' value for all the wind turbines in the offshore wind farm. The corresponding mttf (mean time to failure) is associated with equation 4.17 in the Algorithm Box 4. The 'ttr' and 'tpm' are calculated for every wind turbine that has failed awaiting a repair expedition at the next scheduled maintenance period, as shown in Algorithm Box 4.

4.2.4.5 Justification for the suitability of the exponential distribution

Although there are several mathematical models to statistically evaluate the reliability of a system, the most common are the Weibull and the exponential. These two mathematical models are assessed in the following paragraphs and their suitability is investigated, considering the distribution of the failure rate function when modelling the reliability of offshore wind turbines for the Monte Carlo model, as described in Chapter 4.

The advantages and disadvantages of Weibull and exponential distributions are presented in the following Table and their suitability for offshore wind turbines is investigated.

Table 4.3.a The advantages and disadvantages of a Weibull distribution for its application on offshore wind turbine reliability assessment.

Advantages	Disadvantages
It could be utilised if the failure mechanism is expected to rise over time as it is related to fatigue, wear or some other time/usage based mechanism	It needs three different data parameters, as shown in equation 1 below: and these data is hard to acquire, particularly for offshore wind turbines
It could accommodate rising or falling reliability	If the data used is unreliable then the effect on the mathematical result is substantial

A general form of a three parameter Weibull probability density function is presented below in equation 4.17a:

$$f(x) = \frac{\beta}{\eta}\left(\frac{x-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\eta}\right)^{\beta}} \tag{4.17a}$$

Where:
η =scale parameter, β = shape parameter, γ = location parameter

Table 4.3.b The advantages and disadvantages of an exponential distribution for its application on offshore wind turbine reliability assessment.

Advantages	Disadvantages
It only requires on parameter to be utilised, as shown in equation 4.14 (p. 119)	It assumes that failure rates are constant and don't change with time
This parameter can be forecast reasonably well using stress and other factors to, e.g. predict off-shore wind turbine data from on-shore data	It does not take into consideration the burn-in period and ageing period of the bathtub curve
It is typically used when considering the middle part of the "bathtub" curve when failure rates are often fairly constant	

A key output of this thesis is a prediction of the costs of energy generated, with different simulations to reflect different support and maintenance strategies. The choice between the different mathematical models for the simulation of the reliability of offshore wind turbines has been based on their advantages and disadvantages as presented in Tables 4.3a and 4.3b above.

When simulating the Weibull distribution then it is necessary to have adequate hard data from industrial data logging or extensive statistical data, in order to define the required parameters η, β and γ, as shown in equation 4.17a above. However, it is not always possible to gain access to such extensive data, and in fact they do not exist for offshore wind turbines since no published report has been released to date that presents failure rate data. That is the reason why failure rate data for offshore wind turbines have been evaluated based on published data on onshore wind turbines, as shown for the reliability model in Chapter 4 (p. 96).

Observed reliability data from wind turbines in operation is highly desirable because they implicitly account for all actual usage and environmental stresses, however there are often missing details associated with failure data logging.[164] The general practice in failure data logging is to record only cumulative failures and operating times, which results in failure data from the field is usually being tainted, incomplete and lack sufficient detail.[165] In particular, the actual times-to-failure are often not recorded and the data are grouped together and presented as a total number of failures and a cumulative number of operating hours.[164] This lack of detail is often a result of maintenance record-keeping policies. The above observation imposes a difficulty to determine whether the wind turbine failure function varies with time or is constant.[164]

When considering an exponential distribution, then the failure rate function for offshore wind turbines are considered to be constant in time, i.e. considering the second stage of a typical bathtub curve as shown in Figure 4.9 in Chapter 4 (page 118). The above assumption however does not allow for the simulation of offshore wind turbine failures that happen during the ‘burn-in’ stage (first period) of the bathtub curve. On the other hand, this burn-in period of an offshore wind farm is covered by a warranty contract with the manufacturer and supplier of the offshore wind turbines. Typically, wind turbine manufacturers offer a 2 or 3 year warranty period (which is typically extended up to 5 years at an added cost of the wind turbine price), where failures of components are considered to be the manufacturer's obligation to address, while normal 'wear and tear' related failures are the operator's obligation. The above observation leads to the conclusion that wind turbine failure during the burn-in period are simply not being dealt with by the operator and therefore should not be simulated for the Monte Carlo model, but only failures related to wear and tear (as happens during the second stage of the bathtub curve) should be taken into consideration.

Summarising the above considerations it can be concluded that the choice of the exponential distribution for the simulation of the reliability of offshore wind turbines could be utilised. This is achieved by considering the following key point:

a) There is a significant "burn-in" period, but failures in this period are generally covered by warranties provided by the turbine vendor, and the cost of these warranties are included in the CAPEX of the offshore wind farm.

b) In addition many vendors offer an extended period warranty at an additional price, which is included in the CAPEX of the offshore wind farm.

c) For most of the expensive failures, e.g. blades and gearbox, the modules in question are failing well before they get to the ageing part of the bathtub. A typical time to failure for a gearbox is 6 to 8 years.[166]

d) Most of the failures that the model simulates are likely to be in the middle (relatively constant) part of the bathtub curve

The observations made in the previous paragraphs indicate that the assumption of utilising an exponential distribution for the failure rate function of offshore wind turbines for the Monte Carlo model is adequately addressed as it is based on two factors, i.e. the lack of available industrial data and also the extended warranty during the burn-in period of a typical bathtub curve. However, should reliability data from offshore wind turbines come available, a Weibull distribution could be used and the impact on the predictions explored.

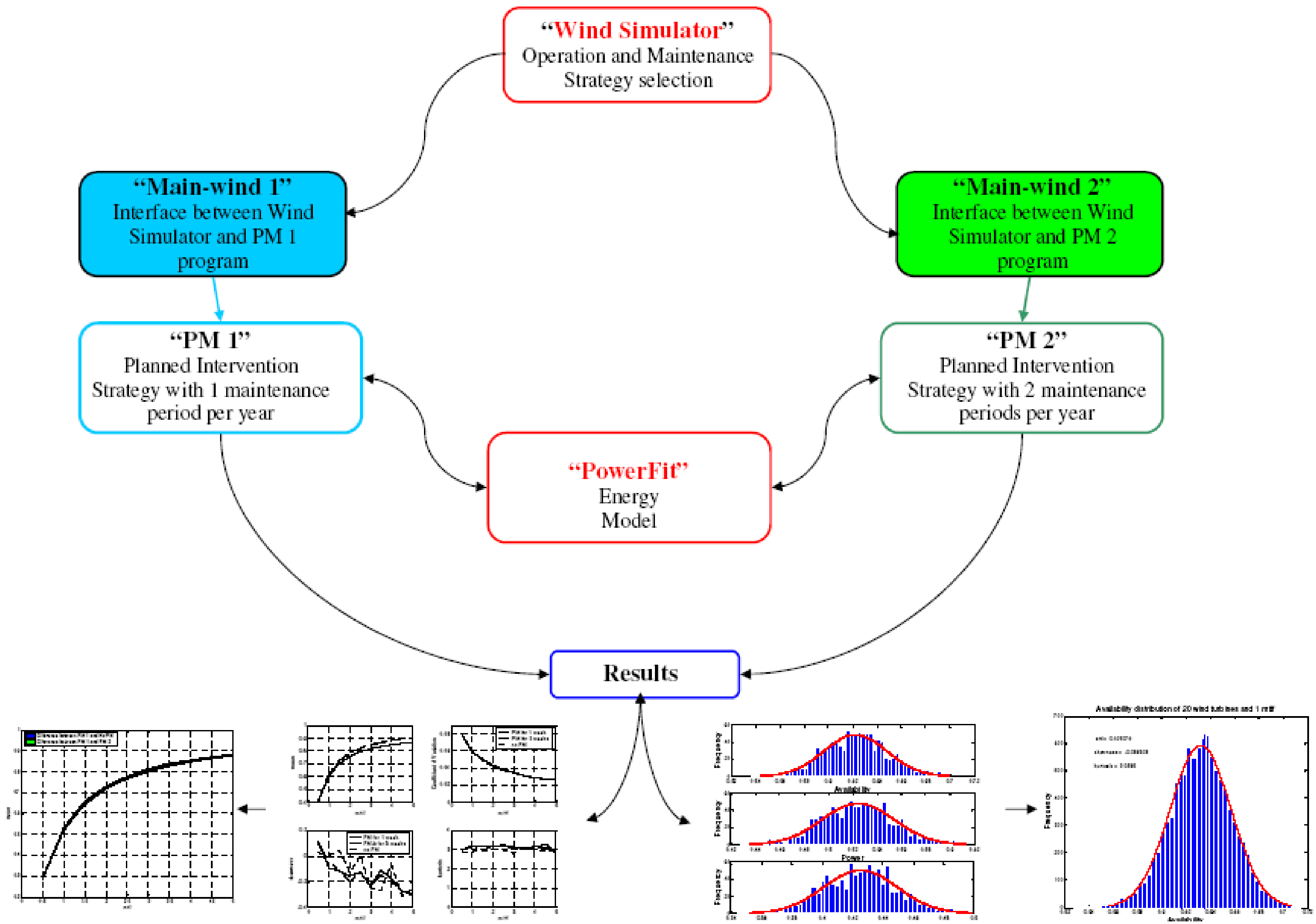

Figure 4.11 Schematic diagram of the computer programs for the simulation of planned intervention maintenance policy of offshore wind farms

4.3 Structure of planned intervention maintenance policy model

Having defined the reliability, the economic, the energy and Monte Carlo models the next step was to integrate the models into the core O&M model in order to simulate the planned intervention maintenance policy applied to offshore wind farms. Figure 4.11 uses a schematic flow diagram to show how the planned intervention maintenance policy is simulated using a series of programs that call upon the previously developed models and how they interact with each other. The programming language that was used to develop the algorithms of the programs is the Mathworks Matlab® versions 6.x and 7.x, with statistical toolboxes and guided user interface toolboxes integrated.

Two different scenarios of the planned intervention maintenance policy have been investigated, and two core O&M computer simulation programs have been developed, namely ‘PM 1’ and ‘PM 2’, which are able to consider one or two scheduled maintenance visits per year to each wind turbine in an offshore wind farm, as previously explained in Chapter 3. In both scheduled maintenance scenarios the maintenance visits are defined as occurring between the beginning of May and the end of October, in order to avoid bad weather and high sea states, this period being defined through analysis, as previously explained for the energy model and detailed in Appendix C. The main blocks in Figure 4.11 are: Wind Simulator; Main-Wind 1 and Main-Wind 2; PM 1 and PM 2; PowerFit, and Results and these are described as follows:

4.3.1 Wind Simulator program

Wind Simulator is a user interface program that allows the user to define key input parameters needed in the analysis of the planned intervention maintenance policy. This program was developed using the Matlab® Compiler for Graphical User Interface (GUI). The Matlab algorithm of the Wind Simulator program is presented in Appendix L. The parameters set by the user are as follows:

1. **Select a scenario**. Select one or two scheduled maintenance visits per year for the planned intervention maintenance policy, i.e. select either ‘PM 1’ or ‘PM 2’.

2. **Setting the inputs parameters**. Define the input parameters for the offshore wind farm, including the number of wind turbines and their power rating, as shown in Algorithm Box 5.

3. **Set the number of Monte Carlo simulations**. Define the number of Monte Carlo iterations to be used by the ‘PM 1’ and ‘PM 2’ programs. A large number of iterations minimises statistical error but increases computational time. Analysis of the appropriate number of simulations is presented in the following Chapter.

4. **Assess the results**. This defines the presentation of the results, which may be in graphical form. The range of results that can be provided includes the average wind farm availability, cumulative energy output, levelised production cost of energy and CO2 emissions.

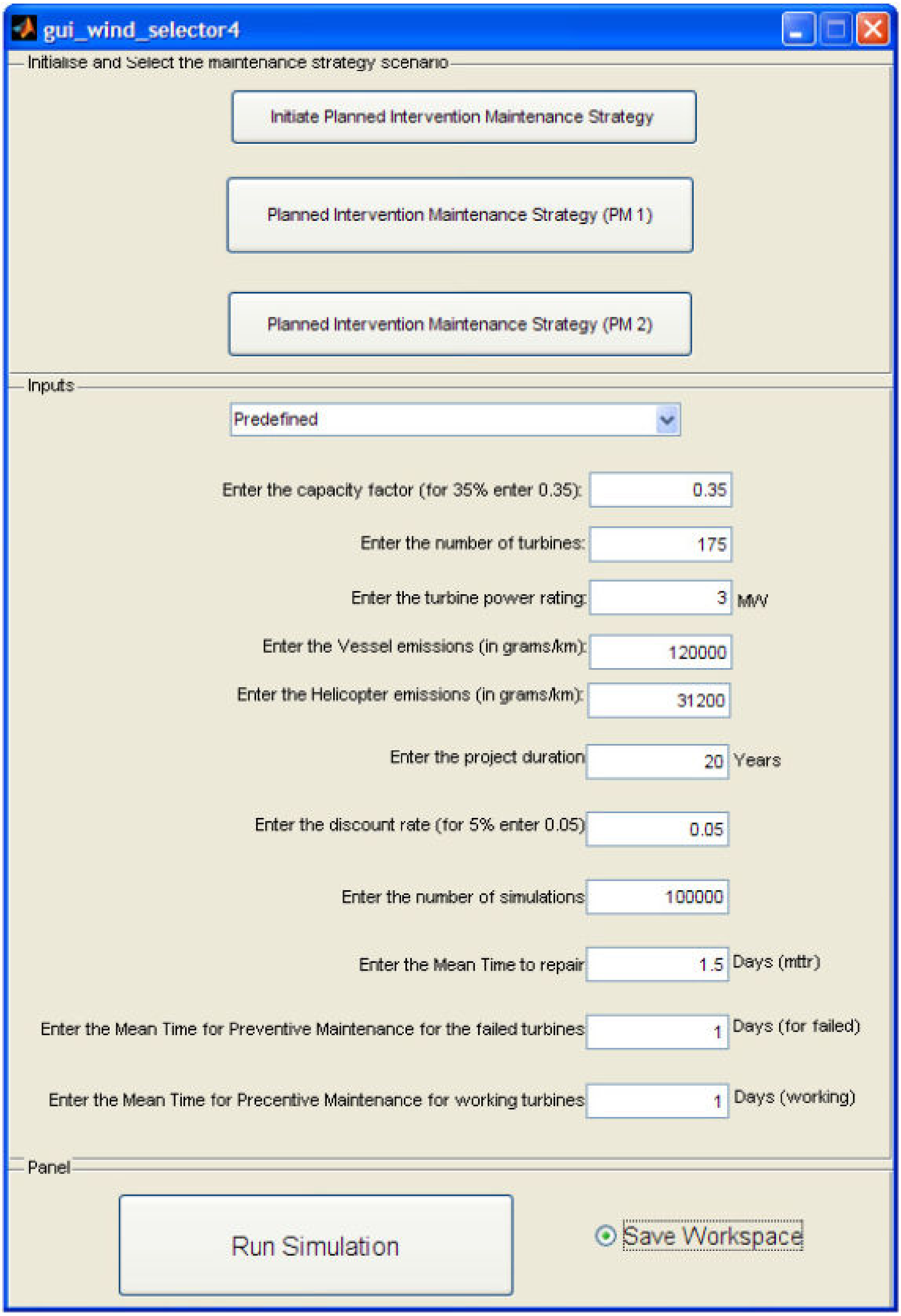

Figure 4.12 The Guided User Interface program developed to input the parameter values.

Algorithm Box 5: Input of different parameters for the planned intervention maintenance strategy using the 'Main-Wind' program

```
turbines = input ('Enter the number of the wind turbines in the
                  windfarm:  ');

turbine_rating = input ('Enter the turbine power rating (for 5 MW
                        enter 5):    ');

capacity_factor = input ('Enter the expected capacity factor of the
                         wind farm (for 35% enter 0.35):    ');

years = input ('Enter the project duration (in years): ');

discount = input ('Enter the discount rate (for 5% discount enter
                  0.05):  ');

simulations = input ('Enter the number of the simulations:  ');

Distance = input ('Enter the distance to shore (in km): ');

Heli_emissions = input ('Enter the Helicopter emissions
                       (in grams/km):  ');

Vessel_emissions = input ('Enter the Boat emissions (in
                         grams/km):');

mttr = input ('Enter the mean time to repair for the failed
              turbines (mttr for 3.5 days enter 0.0095):   ');

mtpm = input ('Enter the mean time for preventive maintenance for
             the failed turbines (mtpm for 1 day enter 0.00275):');

mtpm_work = input ('Enter the mean time for preventive maintenance
                  for the working turbines:   ');
```

After the determination of the input parameters of the planned intervention maintenance policy, the following steps are performed automatically from the developed programs until the results are produced. These automatically performed tasks are explained in detail in the following paragraphs.

4.3.2 Main-Wind 1 and Main-Wind 2 programs

The user interface Wind Simulator program passes the information to either Main-Wind 1 or Main-Wind 2 programs depending upon which planned intervention maintenance policy scenario the user has selected. The purpose of the Main-Wind 1 and Main-Wind 2 programs are to interface between the Wind Simulator user interface and the core O&M programs namely ‘PM 1’ and ‘PM 2’ programs, to relate the input parameters to each specific maintenance scenario.

Further, the Main Wind programs collect the output results after the end of all the simulations in different matrices, and pass the information to the Results programs for the development of the graphical representation of the results, which are explained further in this Chapter.

4.3.3 ‘PM 1’ and ‘PM 2’ programs

The ‘PM 1’ or ‘PM 2’ programs run automatically once they have received the appropriate information from the Main-Wind 1 or Main-Wind 2 respectively. The purpose of the ‘PM 1’ and ‘PM 2’ programs is to use the information supplied by Main-Wind 1 and Main-Wind 2 to obtain results using the developed models described previously, i.e. the reliability, the economic, the energy and Monte Carlo models. The results are in terms of wind farm availability, cumulative energy output, levelised production cost of energy etc, as described in the SADT diagram in Chapter 3 (Figure 3.4).

Figure 4.13 shows a schematic diagram of ‘PM 2’ program which is used here to describe functionality since ‘PM 1’ is essentially the same program with minor differences and is presented in Appendix H.

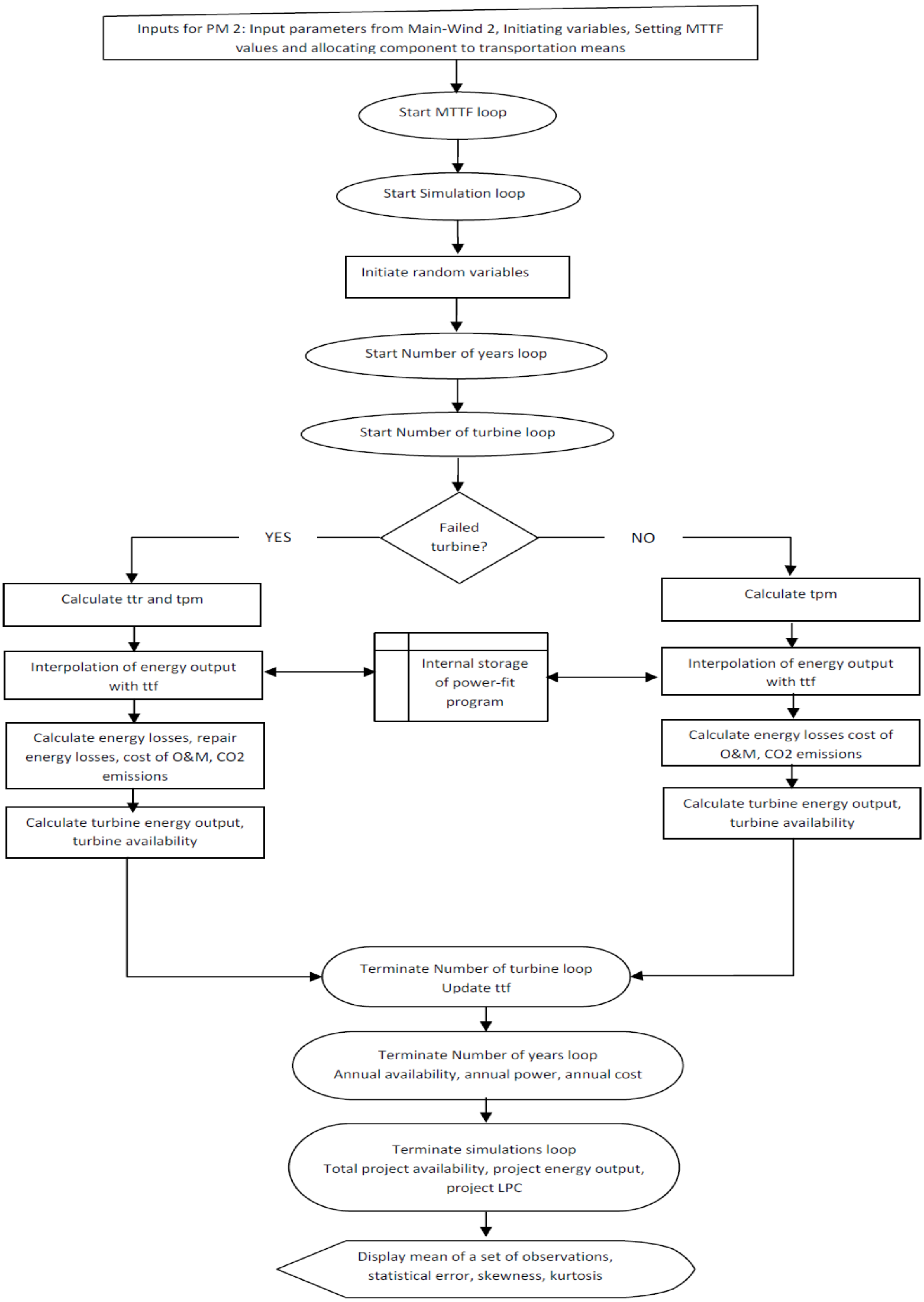

Figure 4.13 The structure of Matlab® code for Planned Intervention with two scheduled maintenance periods per year for all the wind turbines

When considering 'The inputs for PM 2' Box in Figure 4.13, there are three initial tasks that take place; the initiation of variables, the assignment of MTTF values to the wind turbine components, and for each component in a wind turbine there is a transport allocation, i.e. ship or/and helicopter. These tasks are detailed in the following paragraphs.

4.3.3.1 Initiating variables

Considering 'The inputs for PM 2' Box in Figure 4.13, a number of different actions are performed to set and 'initiate' the variables, e.g. ttf, and a number of different parameters, e.g. turbine availability, for the simulation of planned intervention maintenance policy, as also seen in Algorithm Box 6. 'Initiating' a variable means that the variable is defined in the algorithm as a variable matrix with appropriate dimensions and allocated computer memory space to optimise computer processing time.

Algorithm Box 6 also shows how the different variables are initiated by the 'PM 2' program, e.g. ttf is initiated as a one column multi row matrix, which is exactly defined by the number of wind turbines. Similarly other variables are initiated in the same way.

Algorithm Box 6: Allocation of memory space to the variables and parameters for the simulations

```
%-----------------------Variables Initiation----------------------%
ttf = zeros(turbines,1);
ttr = zeros(turbines,1);
tpm = zeros(turbines,1);
power_loss = zeros(turbines,1);
repair_power_loss = zeros(turbines,1);

%------------------------Availabilities---------------------------%
turbine_avail = zeros(turbines,1);
annual_avail = zeros(periods,1);
proj_avail = zeros(simulations,1);
k2 = zeros(turbines,1);
k1 = zeros(turbines,1);
annual_k = zeros(periods,1);
annual_k1 = zeros(periods,1);
proj_k = zeros(simulations,1);
proj_k1 = zeros(simulations,1);

%-----------------------------Power-------------------------------%
turbine_power = zeros(turbines,1);
annual_power = zeros(periods,1);
proj_power = zeros(simulations,1);

%--------------------Cost of maintenance--------------------------%
C_om = zeros(turbines,1);
C_om1 = zeros(turbines,1);
C_om2 = zeros(turbines,1);
annual_C_om = zeros(periods,1);
```

4.3.3.2 Setting MTTF values for wind turbine components

Considering 'The inputs for PM 2' Box in Figure 4.13, the values of MTTF are defined for a item as a percentage of the total MTTF for the whole wind turbine, as shown in Algorithm Box 7. The value of MTTF for every wind turbine component is defined by analysis carried out by the reliability model, described earlier in this chapter in section 4.2. Further details on the MTTF of wind turbine components are given in Appendix E.

4.3.3.3 Allocating transportation means to wind turbine components

Having defined the MTTF values for each component, the next step in the program is to allocate each item with its own transportation method i.e. ship or helicopter. The allocation process considers the repairs and maintenance requirements, e.g. tools and personnel, the size of any replacement item, and accessibility requirements, as detailed in Appendix B. For example large items such as gearboxes, blades and generators will require a large vessel, whilst smaller items such as power electronic modules and bearings could use a helicopter. The assignment of wind turbine items to different transportation means is given in Algorithm Box 7.

Algorithm Box 7: Assigning mean time to failure (MTTF) values for each wind turbine component based on the WMEP database

```
MTTF1 = (mttf * 0.03);      % Mean Time To Failure of the Housing
MTTF2 = (mttf * 0.068);     % Mean Time To Failure of the Yaw System
MTTF3 = (mttf * 0.043);     % Mean Time To Failure of the Gearbox
MTTF4 = (mttf * 0.06);      % Mean Time To Failure of Other
                              components
MTTF5 = (mttf * 0.024);     % Mean Time To Failure of the Drive
                              Train
MTTF6 = (mttf * 0.216);     % Mean Time To Failure of the Control
                              System
MTTF7 = (mttf * 0.219);     % Mean Time To Failure of the Electric
                              System
MTTF8 = (mttf * 0.036);     % Mean Time To Failure of the Generator
MTTF9 = (mttf * 0.101);     % Mean Time To Failure of the
                              Blades/Pitch
MTTF10 = (mttf * 0.095);    % Mean Time To Failure of the Hydraulics
MTTF11 = (mttf * 0.05);     % Mean Time To Failure of the Rotor Hub
MTTF12 = (mttf * 0.058);    % Mean Time To Failure of the Mechanical
                              Brakes

%-----Establishing the transportation means for each component----%


MTTF_Heli = (MTTF1 + MTTF2 + MTTF4 + MTTF6 + MTTF7 + MTTF10 +
             MTTF12)/mttf;

MTTF_Boat = (MTTF3 + MTTF5 + MTTF8 + MTTF9 +MTTF11)/mttf;
```

This section of the 'PM 2' program (Algorithm Box 7) could be edited by the operators of the wind farm in order to change the values of item MTTF according to the maintenance history of the offshore wind farm, which will be built upon the maintenance experience over the years of operation, as explained in the previous Chapter for the AMP dynamic nature of the planned intervention maintenance policy.

After the end of the tasks for 'The inputs for PM 2' Box in Figure 4.13, The program initiates four different loops, embedded within each other, and are known as the:

1. **MTTF loop** (Green Arrow on Figure 4.13)
2. **Simulations loop** (Yellow Arrow on Figure 4.13)
3. **Number of Years loop** (Red Arrow on Figure 4.13)
4. **Number of Turbines loop** (Purple Arrow on Figure 4.13)

These loops are explained in detail in the following paragraphs.

4.3.3.4 MTTF loop (Green Arrow on Figure 4.13)

After the completion of the tasks for 'The inputs for PM 2' box, then the first loop i.e. the MTTF loop is initiated, as shown in Figure 4.13. The MTTF loop executes the range of MTTF values for the offshore wind turbines. The range of MTTF is defined by the reliability model. Upon initiation of the MTTF loop, the first value in the range of wind turbine MTTF is selected automatically from the 'PM 2' program and the information fed to the following loops, i.e. the program defines the first MTTF value e.g. 0.25 years, and feeds this value to the following loops for calculations of the output results.

Algorithm Box 8: Initiation of the MTTF loop (Green Arrow on Figure 4.13)

```
%-------------------Counting time of simulation-------------------%

tic

for i=1:10

%----------Ten different values of mttf are simulated-------------%

mttf(i) = i*0.25;

%-----------Collecting data from all the inner loops-------------%

[avail(i,:),power(i,:),lpc(i,:),TOC1(i,:),CO2_Helicopter(i,:),
CO2_Boats(i,:)] = pm2(mttf(i),mttr,mtpm,mtpm_work,turbines,years,
                  discount,capacity_factor,turbine_rating,
                  powerfit_season1_array,powerfit_season2_array,
                  simulations,Distance,Heli_emissions,
                  vessel_emissions);

%--------------Counting the number of iterations------------------%
i

%------------------------Ending the loop--------------------------%
end

toc
```

At this stage the model calculates the outputs for the first value of MTTF in the range, the results are stored in a matrix and the next value of wind turbine MTTF is automatically selected from the MTTF range to calculate the new set of results. This sequence is continued until all the wind turbine MTTF values in the range are simulated. This process is shown in Algorithm Box 8, where the initiation of the first loop is presented.

4.3.3.5 Simulations loop (Yellow Arrow on Figure 4.13)

This loop simulates the Monte Carlo model through the ‘PM 2’ program using equation 4.17, as seen in Algorithm Box 9. The Simulations loop defines the number of iterations needed for the Monte Carlo model and calculates the statistical parameters of the stochastic processes, i.e. the mean, the standard deviation, the skewness, the curtosis and the statistical error. These statistical parameters are assessed in order to analyse the accuracy of the outputs of the model, this process being explained in the following Chapter at the verification of output results.

Algorithm Box 9: Initiation of the Simulations loop (Yellow Arrow) and the Number of Years loop (Red Arrow)

```
%------Simulations loop:   For 'j' number of simulations----------%

for j = 1:simulations;

%-------------Generation of random variables----------------------%

X = rand(turbines,1);
ttf = -mttf * (log(X));


%---Two periods of maintenance per operational year (Years loop)--%

for m = 1:periods;

ttf = ttf - 0.5;      % ttf reduced by 0.5 indicating each 6 month
                        period.

if rem(m,2)==0;       % Checks if m is odd or even number and
                        assigns a period. 'Rem' command treats
                        period 2 as 1st.
```

At the end of every simulation, the Simulations loop stores the calculated outputs in different matrices and at the end of all the simulations, the average value of each output is evaluated and stored in a matrix.

4.3.3.6 Number of Years loop (Red Arrow on Figure 4.13)

For every iteration number from the Simulations loop an inner loop is initiated, called the Number of Years loop. This loop identifies the number of years for the offshore wind farm operation (usually 20 years of operation). For every iteration of the Number of Years loop, i.e. for every operational year that passes, the time to failure of every offshore wind turbine is reduced by one year as seen in Algorithm Box 9. Specifically, for the ‘PM 2’ program, the time to failure is reduced by half a year for every scheduled maintenance period that ends. For every iteration of the Number of Years loop the outputs are stored in an annual matrix database.

4.3.3.7 Number of Turbines loop (Purple Arrow on Figure 4.13)

For every iteration of the Number of Years loop the next inner loop, the Number of Turbines loop, is initiated. The Number of Turbines loop investigates each wind turbine whether or not it has failed according to the allocated time to failure. Two different pathways are then possible; the wind turbine has failed or the wind turbine is operational, as shown in Figure 4.13:

4.3.3.8 The wind turbine has failed

In this pathway the economic model and the energy model interact with the Monte Carlo model to calculate the results in terms of wind turbine availability, energy output and energy losses, cost of maintenance expeditions and CO2 emissions.

The energy model calculates the wind energy produced by the wind turbine until the time it failed by considering the energy losses due to downtimes, as shown in Algorithm Box 10. The economic model then calculates the cost of maintenance expeditions for maintenance and repairs, as shown in Algorithm Box 1. The calculation of the CO2 emissions is shown in Algorithm Box 11, based on the assignment of a specific transportation means to the item that has failed. After the failed item has been repaired other critical items are inspected and preventively maintained, e.g. oil change for the gearbox or bearing inspections. After the wind turbine has been repaired and inspected a new time to failure (ttf) is assigned to the wind turbine for the next period. This ttf assignment uses the equations developed for the Monte Carlo model (equations 4.14 to 4.17) and the analysis presented in Appendix G.3 for the mttf of preventively maintained wind turbine system.

Algorithm Box 10: Calculation of the energy output and energy losses

```
%Interaction of the Monte Carlo model with the Energy model for the
calculation of energy output for the failed wind turbines

power_out2 = powerfit_season2_array(floor((multi_presic2) *
             ttf(find(ttf<=0))) + 1);

%---Energy losses due to inspections and preventive maintenance---%

power_loss(find(ttf<=0)) = (multi_month_selection_May) *
                           tpm(find(ttf<=0));

%--------Energy losses due to repair of the wind turbine----------%

repair_power_loss(find(ttf<=0)) = (multi_month_selection_May) *
                                  ttr(find(ttf<=0));
```

4.3.3.9 The wind turbine is operational

In this pathway the energy model and the economic model interact again with the Monte Carlo model to calculate the availability of each wind turbine, the energy output, the cost of expeditions for inspections and preventive maintenance and the associated CO2 emissions, as explained in the previous paragraph.

Algorithm Box 11: Calculation of the CO2 emissions for the maintenance expeditions

```
% Calculation of the CO2 emissions by using a helicopter

k2 = length(ttr(find(ttf<=0)));
CO2_Heli1(find(ttf<=0)) = Heli_emissions * MTTF_Heli * 2 * Distance
                          * k2;

% Calculation of the CO2 emissions by using a vessel

CO2_Vessel1(find(ttf<=0)) = Vessel_emissions * MTTF_Vessel * 2 *
                            * Distance * k2;

% Summing up all the CO2 emissions (For helicopters and vessels)

CO2(find(ttf<=0)) = CO2_Vessel1(find(ttf<=0)) +
                    CO2_Heli1(find(ttf<=0));
```

After the end of each ‘Number of turbines loop’ the results for each wind turbine are stored in an annual matrix as shown in Algorithm Box 12.

Algorithm Box 12: Calculation of the mean of each variable per annum

```
annual_avail(m) = mean(turbine_avail); % Annual Availability

annual_power(m) = sum(turbine_power); % Annual energy output

annual_C_om(m) = sum(C_om); % Annual cost of maintenance tasks

% TOC is the discounted value of the annual costs of maintenance

TOC(m) = (1 / ((1 + discount/2) ^ (-m))) .* annual_C_om(m);

annual_CO2(m) = sum(CO2); % Annual CO2 emissions
```

4.3.4 Results programs

Considering that all the simulations have finished, then the output results are averaged in different matrices, as previously explained for the Monte Carlo model, and the Main-Wind programs collect all simulated results to pass them on to the Results programs. At this stage the graphical representation algorithms can be initiated to illustrate the outputs with the aid of graphs. The outputs that can be derived from the model, as explained for Figure 3.4 in Chapter 3, are in terms of cumulative energy output, cost of unit of energy produced, cost of maintenance, total number of failures serviced, maintenance resources used and CO2 emissions. Different graphical representation algorithms have been developed to illustrate these outputs. An example of a graphical representation algorithm is shown in Algorithm Box 13, where the plotting techniques for the accuracy of results are presented, while the Matlab algorithms for the other Results programs are presented in Appendix L.

Algorithm Box 13: Plotting techniques for accuracy of results and skewness and kurtosis

```
% Plot the graph of LPC against mttf

subplot(221),plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('mean'),grid

% Plot the graph of the Coefficient of Variation against mttf

subplot(222),plot(mttf,lpc(:,2) ./
lpc(:,1)),xlabel('mttf'),ylabel('Coefficient of Variation'),grid

% Plot the graph of skewness of LPC distribution against mttf

subplot(223),plot(mttf,lpc(:,3)),xlabel('mttf'),ylabel('skewness'),
grid

% Plot the graph of kurtosis of LPC distribution against mttf

subplot(224),plot(mttf,lpc(:,4)),xlabel('mttf'),ylabel('kurtosis'),
grid
```

4.4 Limitations of the developed models

As with all software coding, there are limitations and assumptions of the models and programs as follows:

- **The social and environmental costs** that could not be calculated play a significant role for the onshore wind farms, but for the offshore environment are expected to have a reduced effect. The fact that the offshore wind farms are located in the marine environment reduces the social impact in terms of visual (aesthetics) and noise disturbance, as compared to onshore wind turbines. However, the environmental impact of offshore wind farms is higher as compared to onshore wind farms, since they are constructed in shallow waters with high ecological value to marine life. The cost associated with such social and environmental impact can not be calculated.

- **The energy output** of offshore wind turbines is calculated on a monthly basis, using statistical data. For each offshore wind farm site a specific energy output simulation model would apply. That is the reason why 'Power-Fit' program is simulated separately from the core O&M program. In order to be easily accessed and modified to suit every specific site that may be investigated. The operators of the offshore wind farm have the data already collected for the specific site from the wind measurement analysis, which is performed prior to the installation of the wind farm.

- **The repair cost** of the wind turbine items that have failed is chosen to randomly vary with a mean value between 5% and 10% of the initial cost of the item, as suggested and used by authors and studies,[45,70,71,39,72,73] while the initial cost of each wind turbine item being defined by studies reporting on the economical aspects of large wind turbines and offshore wind farms, which in turn is dependant upon the size and power rating of wind turbines.[41,30,61,62,86,108] In reality, however, the cost of repairing a faulty wind turbine component that has been used in the O&M model developed is an approximation of the actual cost. Hard data on the actual cost of component repair could only be obtained from operators of offshore wind farms, which in turn could be used as known input parameters for the O&M model of planned intervention maintenance policy that has been developed in this Chapter.

- The value of **the capacity factor** of the offshore wind farm, used in the simulations was assumed to be constant throughout the projects lifetime, but in reality the capacity factor varies with time and location. Similarly as for the energy output model, wind measurement data from the operators of the offshore wind farm can be inserted to suit every specific location of a wind farm.

- **The availability of maintenance transportation**. The availability of the helicopters and vessels for the maintenance of offshore wind farms has been set to be 100%. The reason is that for the planned intervention maintenance policy the number of helicopters and vessels needed for the maintenance of the wind turbines are clearly identified well before the maintenance expedition commences, and in that respect a higher availability of transportation means could be achieved compared to the corrective maintenance strategy. This observation suggests that the effect of the availability of transportation means for the offshore wind farm will be much lower for the planned intervention maintenance policy as compared to the corrective maintenance practices. The effect of the availability of maintenance transportation is investigated in the following Chapter.

- **The number of scheduled maintenance periods per year** has been established for the investigation of the planned intervention maintenance policy up to two, i.e. two different scenarios are investigated in this thesis having one or two scheduled maintenance periods per year, this being explained by the fact that the maintenance periods should be equally spaced throughout the year, e.g. three maintenance periods per year would mean that one of them should be scheduled for the winter months, which in turn makes the planned intervention maintenance policy highly dependant upon weather conditions, which contradicts one of the main reasons for the use of this maintenance strategy, as has been explained earlier in this Chapter and also in Chapter 3. However, when considering different weather conditions at different locations in the world then more scheduled maintenance periods could be investigated that would lead to different technical and economical solutions.

4.5 Conclusions

The objective of this Chapter was to develop and analyse an O&M model to simulate the planned intervention maintenance policy as a possible solution to the technical challenge of O&M strategies for offshore wind farms. The O&M model has been broken down to sub-models, i.e. the reliability, the economic, the energy and the Monte Carlo model. Each of these sub-models has been detailed in this Chapter and the interaction between them has been explained. Different computer simulation programs have been developed to simulate the O&M model and its sub-models and they are detailed in this Chapter, with the aid of Algorithm Boxes. The Algorithm Boxes give a representation of the algorithm developed behind each program. The verification of the computer simulation programs developed in this Chapter is presented in the following Chapter.

5 Model Validation and Sensitivity Analysis

5.1 Introduction

The computer simulations programs developed in the previous Chapter for the simulation of a planned intervention maintenance policy for offshore wind farms are validated in this Chapter. This has been achieved by comparing the simulation results obtained from the planned intervention maintenance policy model, against results available in literature for the corrective maintenance strategy. Two studies were identified as having published sufficient results to allow such validation to be undertaken; the Opti-Owecs and the DOWEC projects.

A baseline offshore wind farm is established to conduct a sensitivity analysis on the input parameters of the offshore wind farm, in order to give confidence to the output results produced by the programs. Different scenarios for the planned intervention maintenance policy are then used to investigate how the model input parameters affect the wind farm's availability, cumulative energy output, levelised production cost of energy and CO2 emissions. The output results are verified using theoretical background analysis.

5.2 Validation of planned intervention maintenance policy model

To validate the planned intervention maintenance policy computer based model for offshore wind farms, the simulation output results obtained have been compared against results available in the literature. Two projects were identified as having published sufficient results to allow validation to be undertaken. The Opti-Owecs project and the DOWEC project are both large futuristic offshore wind farm projects, for which the corrective maintenance strategy has been applied and results have been published in literature.[70,71,72,73] Published data provided from simulations of these two offshore wind farms was used to validate the planned intervention maintenance policy model. Unfortunately, no offshore wind farm currently uses a planned intervention maintenance policy so it has been necessary to set the model and define the same boundary conditions set for the variables and the same input parameters to represent each project. For example, the time to failure of the offshore wind turbines and the cost of transportation vessels and helicopters were set to have the same values, i.e. defined in the published data. The expectation from the validation process was to ensure that the model results would confirm to the known differences between the two strategies and follow the maintenance theory, previously discussed in Chapter 3.

5.2.1 Validation of model against the Opti– OWECS project

The Opti-OWECS (Optimisation of Offshore Wind Energy Converters) project used state-of-the-art offshore wind turbine technology to investigate practical solutions for O&M practices for a large offshore wind farm, with the primary aim of reducing the electricity cost.[72,73] The European Commission supported the Opti–Owecs project in Framework 4, of the Non-Nuclear Energy Programme JOULE III.[72,73] One of the key objectives of this investigation was to develop a cost model using Monte Carlo simulations primarily to investigate the application of the corrective maintenance strategy. The failure rates of the offshore wind turbines used in the Opti-Owecs project were between 1.43 and 1.79 per year (or $0.558 \leq MTTF \leq 0.698$ in years). The input parameters of the Opti-Owecs project are given in Table 5.1.

Table 5.1 Opti-Owecs project parameters, as obtained from the published study.[72,73]

Parameters	Value
Turbine Power rating	3 MW
Number of Turbines	100
Distance to shore	20 km
real interest rate	5%
Economic lifetime of project	20 years
Capacity factor	30% - 34%
Availability	75%
Wind turbine failure rates per year	1.43 and 1.79
Cost of maintenance vessel (cranes)	25,000 euros (daily rate)
Cost of helicopters or small vessels	5,000 euros (daily rate)
Mean time to repair	1 day
Mean time for preventive maintenance	1 day
Decommissioning	10% of capital investment cost
Capital Investment cost	372 million euros

The input parameters given in Table 5.1 were used as inputs to the planned intervention maintenance policy model and by using the two different scenarios ‘PM 1’ and ‘PM 2’ results were obtained. Figure 5.1 shows wind farm availability, cumulative energy output and LPC of energy, all plotted against wind turbine MTTF, whilst Table 5.2 provides the results in tabulated form.

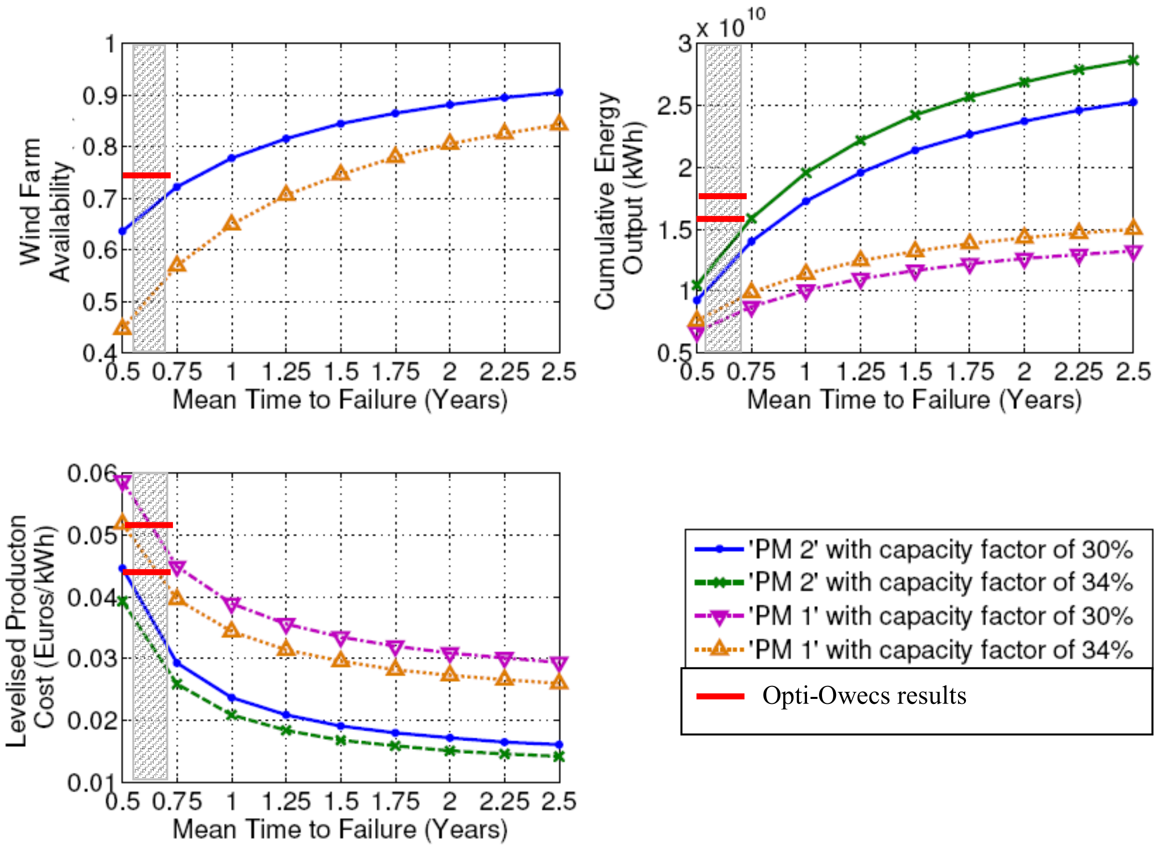

Figure 5.1 Comparison between the planned intervention maintenance policy (both scenarios ‘PM 1’ and PM 2’) and the corrective maintenance strategy (Opti-Owecs project).

Table 5.2 Comparison between the planned intervention maintenance policy (both scenarios ‘PM 1’ and PM 2’) and the corrective maintenance strategy (Opti-Owecs project). The results are listed in order of capacity factor. PI stands for planned intervention maintenance policy and RR stands for corrective maintenance strategy

O&M strategy	**Capacity factor (%)**	**Availability (%)**	**Energy out (kWh*10^{10})**	**LPC (euros/kWh)**
Opti-Owecs (RR strategy)	30	75	1.57	0.051
PM 2 (PI strategy)	30	65 – 70	1.4	0.044
PM 1 (PI strategy)	30	46 – 56	0.87	0.058
Opti-Owecs (RR strategy)	34	75	1.73	0.044
PM 2 (PI strategy)	34	65 – 70	1.59	0.04
PM 1 (PI strategy)	34	46 – 56	0.99	0.051

Considering wind farm availability versus wind turbine MTTF in Figure 5.1 then the two curves representing the ‘PM 1’ (yellow) and ‘PM 2’ (blue) scenarios show that the wind turbine MTTF affects the wind farm availability as expected, since an increase in the wind turbine MTTF would result in increased wind farm availability levels. Both curves are parabolic in their nature (side-opening parabola), the reason being the relationship between wind turbine availability and wind turbine MTTF follows equation 4.12, as previously presented in the Monte Carlo model in Chapter 4 (p. 105). As the curve tends to the horizontal (i.e. MTTF tends to infinity) then the highest value of wind farm availability occurs, as would be expected, i.e.:

$$\lim_{\substack{MTTF \to +\infty \\ MTTR \to 0}} (availability) = \lim_{\substack{MTTF \to +\infty \\ MTTR \to 0}} \left(\frac{MTTF}{MTTF + MTTR} \right) = 1 \tag{5.1}$$

‘PM 1’ curve is lower than ‘PM 2’ as expected since ‘PM 2’ has twice the number of scheduled maintenance visits per year. Now comparing the model results with the Opti-Owecs results (red) then it can be seen that the corrective maintenance strategy offers improved wind farm availability over the planned intervention maintenance policy (i.e. the ‘PM 1’ and ‘PM 2’ models) for 0.558≤MTTF≤0.698, i.e. the shaded area. The wind farm availability is 75% for the Opti-Owecs project, whilst the simulated results for the wind farm availability when considering the ‘PM 1’ scenario are between 46 – 56% and considering the ‘PM 2’ scenario are between 65 – 70%. These results are expected, since the corrective maintenance strategy will always offer greater wind farm availability (considering existing accessibility and reliability levels) over the planned intervention maintenance policy. It has been discussed in Chapter 3 (p. 73-78) that the aim of the planned intervention maintenance policy is to compromise wind farm availability level in order to achieve a cost effective maintenance strategy, i.e. balance cost of maintenance and cost of energy. No corrective maintenance strategy data exists beyond MTTF=0.698 years, therefore comparison at higher wind turbine MTTF values is not possible and nor is it feasible to extrapolate the corrective maintenance strategy results with any degree of confidence.

Now consider the cumulative energy output versus the wind turbine MTTF in Figure 5.1, where two different wind farm capacity factors have been simulated, i.e. 30% and 34%, with two curves representing the 'PM 1' scenario (purple and yellow) and two curves representing the 'PM 2' scenario (blue and green). The curves show that the wind turbine MTTF affects the energy output as would be expected, since an increase in MTTF would give increased energy output. Figure 5.1 also shows that when the capacity factor increases, the energy output also increases as expected, since they are proportional according to equation 4.9, as previously presented in the energy model in Chapter 4 (p. 110). Again, the four curves are each parabolic in nature (side-opening parabola), this being explained because the relationship between the cumulative energy output and wind farm availability is linear, as explained for equation 4.9 (p. 110), consequently the relationship between the energy output and wind turbine MTTF is also parabolic, as described by equation 4.12 (p. 119). When the curve of the cumulative energy output versus the wind turbine MTTF tends to the horizontal, i.e. MTTF tends to infinity, then the cumulative energy output will assume the theoretical maximum energy output over time t, as the energy losses tend to zero.

The two curves representing the 'PM 1' scenario are both lower than the two curves representing the 'PM 2' scenario as expected, since 'PM 2' has twice the number of scheduled maintenance visits per year. Now comparing the model results with the Opti-Owecs results (red) then it can be seen that the corrective maintenance strategy offers higher cumulative energy output over the planned intervention maintenance policy (using the 'PM 1' and 'PM 2' models) for $0.558 \leq MTTF \leq 0.698$, i.e. the shaded area. The energy output of the wind farm when employing the corrective maintenance strategy as compared to the 'PM 2' scenario is 11% greater and as compared to the 'PM 1' scenario is 44% greater. These results were expected since the corrective maintenance strategy offers higher wind farm availability resulting in higher potential for wind energy generation.

Now consider the LPC of energy versus the wind turbine MTTF in Figure 5.1, where two different wind farm capacity factors have been simulated, i.e. at 30% and 34%, then the two curves representing the 'PM 1' scenario (purple and yellow) and the two curves representing the 'PM 2' scenario (blue and green) show that the wind turbine MTTF affects the LPC of energy. This is expected because as the wind turbine MTTF increases the maintenance costs are reduced and LPC of energy decreases. Figure 5.1 also shows that when the capacity factor increases, the LPC of energy also decreases as expected, this being explained by the higher amount of energy output associated with higher capacity factor. The four curves are each equilateral (rectangular) hyperbolic in nature, this being explained because the LPC of energy is proportional to the inversed value of energy output, according to equation 4.8 (p. 108), as previously presented for the economic model in Chapter 4. Consequently the relationship between LPC of energy and wind turbine MTTF becomes also inversed proportional. When the curve of the LPC of energy versus the wind turbine MTTF tends to the horizontal, i.e. MTTF tends to infinity, then the lowest achievable value of LPC of energy occurs, as could be derived from equation 4.8 (p. 108), when considering that repair time tends to zero:

$$\lim_{\substack{MTTF \to +\infty \\ MTTR \to 0}} (LPC) = \frac{Capital\ Investment}{Theoretical\ Maximum\ Energy\ Output} \tag{5.2}$$

The two curves representing the 'PM 1' scenario are both higher than the two curves representing the 'PM 2' scenario, since the higher wind farm availability and higher energy harness achieved by the 'PM 2' scenario would yield lower LPC of energy, as compared to the 'PM 1' scenario. Now comparing the model results with the Opti-Owecs results (red) then it can be seen that the planned intervention maintenance policy simulating the 'PM 2' scenario offers reduced LPC of energy, as compared to the corrective maintenance strategy for 0.558≤MTTF≤0.698, i.e. the shaded area. More specifically, when considering a capacity factor of 30%, the LPC of energy for the corrective maintenance strategy, as compared to 'PM 2' scenario is 15% higher and as compared to the 'PM 1' scenario is 14% lower. For a capacity factor of 34% the corrective maintenance strategy yields an LPC of energy 9% higher, as compared to 'PM 2' scenario and 16% lower as compared to 'PM 1' scenario. It can be concluded from the comparison of these results that when employing the planned intervention maintenance policy with two scheduled maintenance periods per year the cost of energy produced is found to be 9-15% lower as compared to the corrective maintenance strategy applied to the Opti-Owecs project.

5.2.2 Validation of model against the DOWEC project

The DOWEC (Dutch Offshore Wind Energy Converter) project investigated the different input costs, energy output and LPC of energy for a 480 MW offshore wind farm consisting of 80 offshore wind turbines of 6 MW of rating, which is planned to be constructed in the future in the North Sea at a location known as 'NL7'.[70,71] The DOWEC project has simulated the practices of the corrective maintenance strategy applying the Monte Carlo method and using a wind turbine failure rate of 1.55 per year (or MTTF=0.645 years). The input parameters of the DOWEC project are given in Table 5.3.

The input parameters given in Table 5.3 were used as inputs to the planned intervention maintenance policy model and by using the two different scenarios 'PM 1' and 'PM 2' results were obtained. Figure 5.2 shows wind farm availability, cumulative energy output and LPC of energy, all plotted against wind turbine MTTF, while Table 5.4 provides the results in tabulated form.

Table 5.3 DOWEC project parameters, as obtained from the published study.[70,71]

Parameters	Value
Turbine Power rating	6 MW
Number of Turbines	80
Distance to shore	100 km
Annual interest rate	5%
Economic lifetime of project	20 years
Capacity factor	43%
Availability	91.6%
Wind turbine failure rates per year	1.55
Cost of maintenance vessel (cranes)	45,000 euros
Cost of helicopters or small vessels	5,000 euros
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Decommissioning	5.8% of capital investment cost
Capital Investment cost	701 million euros

Now consider the wind farm availability versus the wind turbine MTTF in Figure 5.2 then the two curves representing the 'PM 1' (blue) and 'PM 2' (green) scenarios show that the wind turbine MTTF affects the wind farm availability as expected, since an increase in the wind turbine MTTF would result in increased wind farm availability levels. Both curves are parabolic in their nature (side-opening parabola), this being explained earlier for equation 5.1 (p. 146), in the previous paragraph. The 'PM 1' curve is lower than 'PM 2' curve as expected since 'PM 2' has twice the number of scheduled maintenance visits per year. Now comparing the model results with the DOWEC results (red) then it can be seen that the corrective maintenance strategy offers improved wind farm availability over the planned intervention maintenance policy (using the 'PM 1' and 'PM 2' models) for MTTF=0.645 years, i.e. the shaded area. The wind farm availability is 91.6% for the DOWEC project whilst the simulated results when considering the 'PM 1' scenario are between 49 – 55% and considering the 'PM 2' are between 66 – 70%. The range of results for 'PM 1' and 'PM 2' scenarios reflect a range of wind turbine MTTF values between 0.55 and 0.70 in years. These results are expected since the corrective maintenance strategy will always offer greater wind farm availability, as previously explained in paragraph 5.2 (p. 143-153) in this Chapter. There is no corrective maintenance strategy data for wind turbine MTTF beyond 0.645 years, therefore comparison at higher wind turbine MTTF values is not possible and nor is it feasible to extrapolate the corrective maintenance strategy results with any degree of confidence.

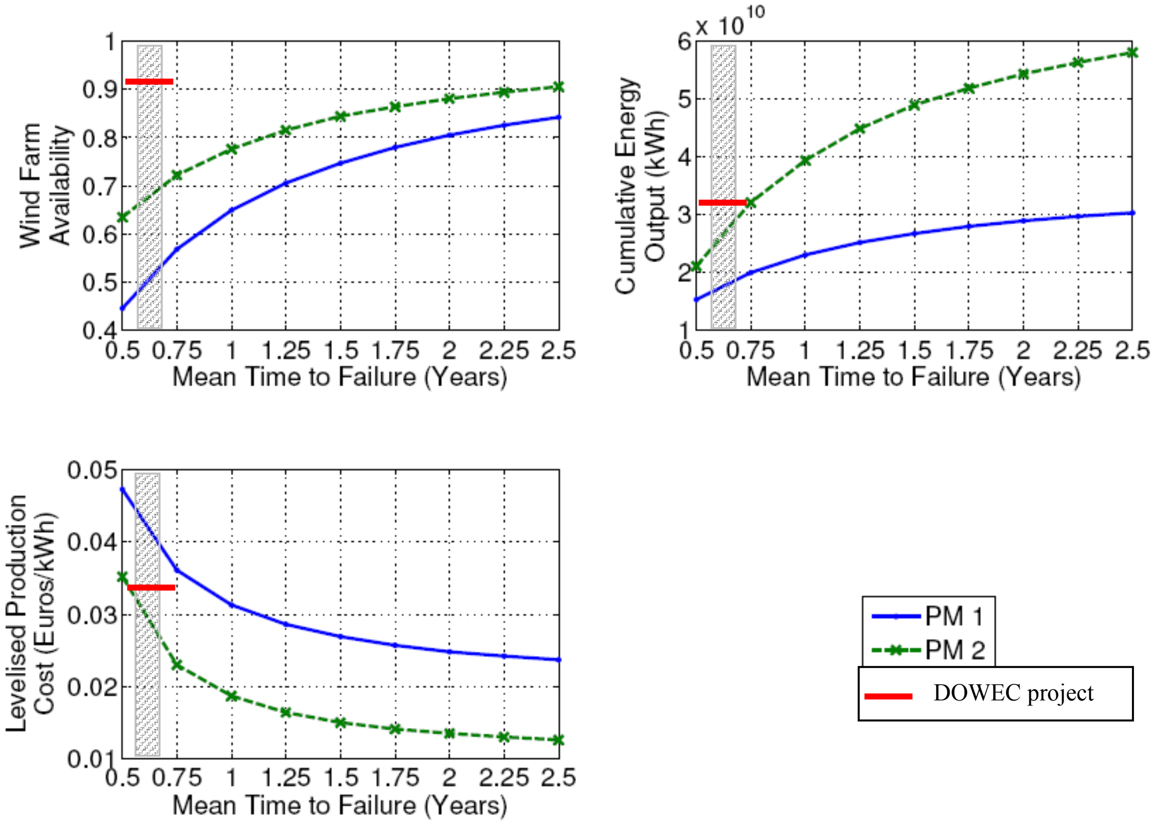

Figure 5.2 Comparison between the planned intervention maintenance policy (both scenarios 'PM 1' and PM 2') and the corrective maintenance strategy (DOWEC project).

Table 5.4 Comparison between the planned intervention maintenance policy (both scenarios 'PM 1' and PM 2') and the corrective maintenance strategy (DOWEC project).

O&M strategy	Availability (%)	Energy out (kWh*10^{10})	LPC (euros/kWh)
DOWEC (Reactive response strategy)	91.6	3.296	0.0338
PM 1 (Planned intervention strategy)	49 – 55	1.62 – 1.79	0.036 – 0.045
PM 2 (Planned intervention strategy)	66 – 70	2.6 – 3.1	0.028 – 0.032

Now consider the cumulative energy output versus the wind turbine MTTF in Figure 5.2, where the two curves representing 'PM 1' (blue) and 'PM 2' (green) scenarios show that the wind turbine MTTF affects the energy output. This is expected since an increase in wind turbine MTTF would give increased energy output. Again the two curves are parabolic in nature (side-opening parabola), this being explained earlier in paragraph 5.2 (p. 143-153). The curve representing the 'PM 1' scenario is lower than the curve representing the 'PM 2' scenario as expected, since 'PM 2' has twice the number of scheduled maintenance visits per year. Now comparing the model results with the DOWEC results (red) then it can be seen that the corrective maintenance strategy offers higher cumulative energy output over the planned intervention maintenance policy (using the 'PM 1' and 'PM 2' models) for MTTF=0.645 years. The total energy output for the DOWEC project is 3.296 * 10^{10} kWh, which is 46 - 51% higher as compared to the 'PM 1' scenario and between 6 – 22% higher as compared the 'PM 2' scenario. These results reflect the effect of higher wind farm availability achieved when employing the corrective maintenance strategy for the DOWEC project.

Now consider the LPC of energy versus the wind turbine MTTF in Figure 5.2, then the two curves representing the 'PM 1' and 'PM 2' scenarios show that the wind turbine MTTF affects the LPC of energy. This is expected because as the wind turbine MTTF increases the maintenance cost is minimised, resulting in increased LPC of energy. The two curves are equilateral (rectangular) hyperbolic in nature, this being explained earlier for equation 5.2, in paragraph 5.2. The curve representing the 'PM 1' scenario is higher than the curve representing the 'PM 2' scenario, since the higher wind farm availability and higher energy harness achieved by the 'PM 2' scenario would yield lower LPC of energy, as compared to the 'PM 1' scenario. Now comparing the model results with the DOWEC results (red) then it can be seen that the planned intervention maintenance policy simulating the 'PM 2' scenario offers reduced LPC of energy, as compared to the corrective maintenance for MTTF=0.645 years, i.e. the shaded area. More specifically, the LPC of energy for the corrective maintenance strategy is 6.5 – 25% lower as compared to the 'PM 1' scenario and 5 – 12% higher as compared to the 'PM 2' scenario.

5.2.3 Summary of validation process

The computer programs developed for the simulation of planned intervention maintenance policy model for offshore wind farms have been validated against published data from two different projects (Opti-Owecs and DOWEC project) which have both simulated the corrective maintenance strategy. Comparison of the results between the planned intervention maintenance policy and the published results from the two projects show that they are comparable. Considering the results from the 'PM 1' scenario the availability of the offshore wind farms and the total energy output are found to be significantly lower as compared against the corrective maintenance strategy results from both projects. Furthermore, the LPC of energy using the 'PM 1' scenario is found to be 15% on average higher, as compared against the LPC of energy from the corrective maintenance strategy for both projects, which indicates consistency of the obtained results from the planned intervention maintenance policy models. Furthermore, considering the results obtained from the simulation of the 'PM 2' scenario, the LPC of energy is found to be 5 – 15% lower, as compared against the corrective maintenance strategy results for both projects.

5.3 Verification of planned intervention maintenance policy model

The purpose of the verification of the planned intervention maintenance policy model was to carry out a sensitivity analysis to give added confidence to the developed computer programs. The verification of the planned intervention maintenance policy model was achieved by establishing a baseline offshore wind farm to carry out a sensitivity analysis on the input parameters of the model, as shown in Figure 3.4 in Chapter 3 (p. 86). Each input parameter of the planned intervention maintenance policy model is varied through a range of values in order to investigate how the model reacts.

5.3.1 Establishment of the baseline

The offshore wind farm that represents the baseline of this study is the London Array offshore wind farm, located 46 km off the coast of Kent and Essex in the UK. London Array has been chosen because it represents a near future large offshore wind farm, currently under construction.

Table 5.5 Baseline offshore wind farm parameters.[92]

Parameters	Value
Turbine Power rating	3.6 MW (Siemens)
Number of Turbines	175
Distance to shore	46 km
Annual interest rate	5%
Economic lifetime of project	20 years
Capacity factor	45%
Cost of maintenance vessel (cranes)	25,000 pounds (daily rate)
Cost of helicopters or small vessels	5,000 pounds (daily rate)
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Decommissioning	2.5% of capital investment cost
Capital Investment cost	1.96 billion pounds

The commissioning date of the first phase of the London Array project is in 2012, which will consist of 175 wind turbines giving a total power output of 630 MW. Further details of the London Array offshore wind farm are presented in Table 5.5.[92]

5.3.2 Sensitivity analysis of the developed model

The baseline offshore wind farm will be used to carry out a sensitivity analysis for verification purposes on the input parameters listed below and assess how the outputs in terms of mean wind farm availability, cumulative energy output, LPC of energy and CO2 emissions are affected:

- Number of Monte Carlo simulations
- Capacity factor
- Number of wind turbines
- Power rating of wind turbines
- Number of years
- Accessibility
- Interest rate
- CAPEX
- Decommissioning costs
- Cost of vessels and helicopters
- Distance to shore
- Transportation emissions

5.3.3 The effect of the number of Monte Carlo simulations

The number of Monte Carlo simulations defines the accuracy of the outputs of the planned intervention maintenance policy model. There is a fine balance between the number of simulations and the statistical error in the calculated results. Figure 5.6 shows the calculation of the mean availability of the baseline offshore wind farm and the calculated statistical error, skewness and kurtosis of the wind farm availability distribution for 5 different numbers of simulations, i.e. 10, 100, 1000, 10000 and 100000 cycles. The results in Figure 5.6 are calculated based on the parameters of the baseline offshore wind farm. The MTTF of the wind turbines has been varied between 0.25 and 2.5 in years (x-axis).

The statistical error in Figure 5.6(a) shows the error of the output result and is calculated by considering the standard deviation divided by the square root of the sample size (number of simulations). Further details on the equations used for the calculation of the statistical error, skewness and kurtosis are presented in Appendix G.2. Figure 5.6(a) shows that the calculated statistical error for 10,000 simulations and above becomes less than 0.5% and its variation over the MTTF range is minimised, which indicates that the results yield acceptable level of accuracy, as detailed by Negra et al 2007.[49]

Graphs (b) and (c) in Figure 5.6 show the skewness and kurtosis of the wind farm availability distribution. The skewness is the measure of the symmetry (around the mean) of a statistical distribution and the kurtosis is the measure of the deviation of the distribution from a normal distribution. Further details for the skewness and kurtosis and the equations used for their calculations are presented in the Definitions sections of this thesis and also in Appendix G.2. Now consider the Central Limit theorem, when the number of simulations increases then the skewness and kurtosis should approach zero and three respectively, thereby representing a normal distribution. It can be observed in graphs (b) and (c) in Figure 5.6 that for 100,000 simulations the skewness becomes zero and kurtosis becomes three, and their variation across the range of MTTF is minimised.

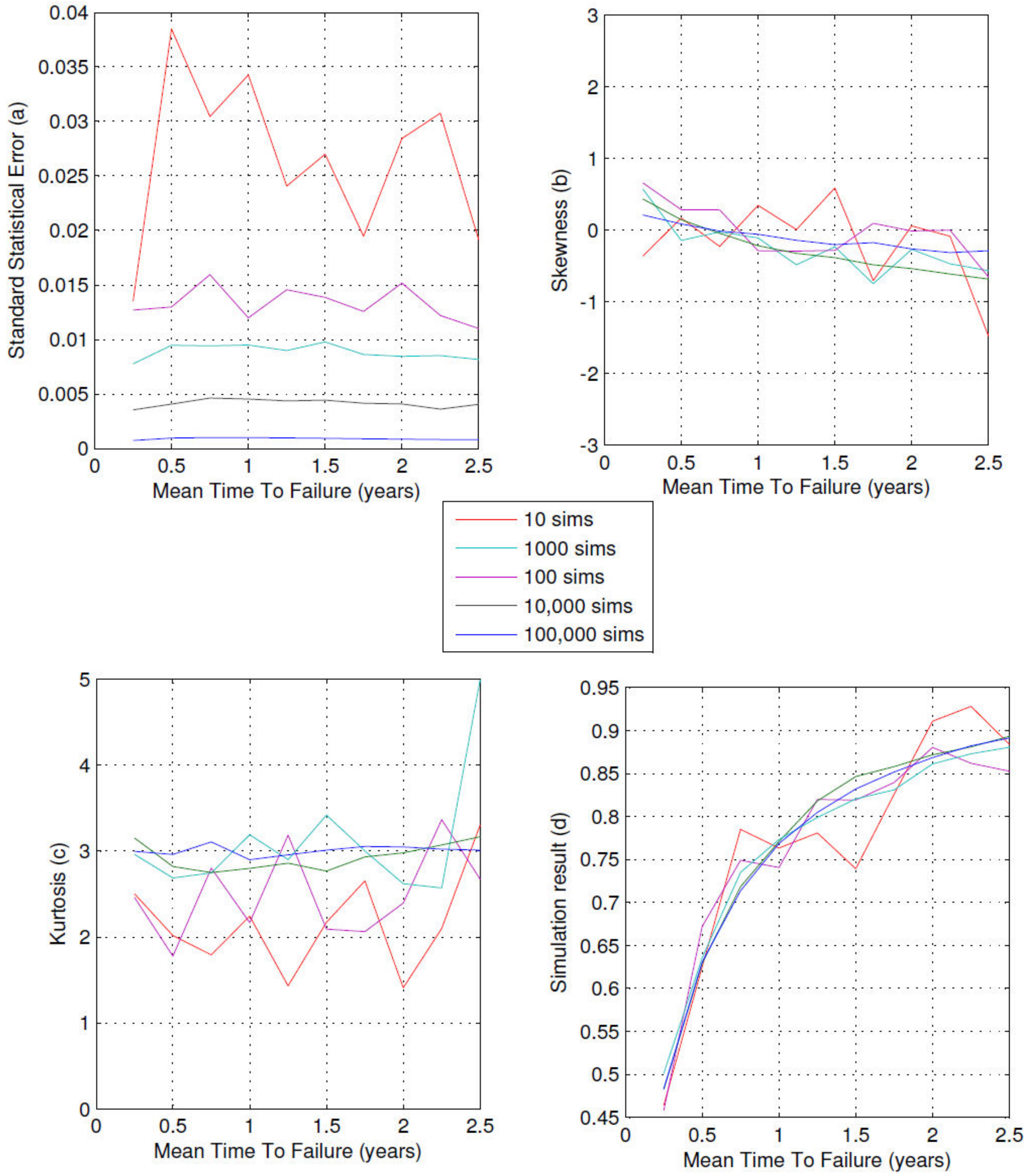

Figure 5.6 Error calculation and accuracy of results for the Monte Carlo simulations of the developed algorithms

A significant observation that is made for Graph (b) in Figure 5.6 is that as the wind turbine MTTF increases then the skewness of the distribution tends to get negative values, regardless of the number of simulations achieved. A negative skewness indicates that the data from the distribution of the wind farm availability are spread out more to the left of the mean value of the distribution, as detailed in Figure Def.1 in the

Definitions section of this thesis. This observation can be explained by considering that the wind farm availability has boundary limits between zero and one, which indicates that as the wind turbine MTTF increases then the mean value of wind farm availability will tend to the boundary limit of 1 and consequently the boundary effect on the spread of data of the availability distribution would be pushed to the left of the mean value. Similarly when considering that the wind turbine MTTF tends to zero then the skewness of the distribution tends to positive values.

Now consider graph (d) in Figure 5.6 for the mean wind farm availability versus wind turbine MTTF. It can be observed that for 100,000 simulations the variation across the range of MTTF is minimised significantly as compared to lower number of simulations, and the resulting curve for 100,000 simulations is of parabolic nature, as would be expected, this being previously explained in paragraph 5.2 of this Chapter.

Figure 5.7 shows an example of a histogram of the distribution for the mean wind farm availability of the baseline offshore wind farm using 100,000 simulations, where the values of the mean, the standard deviation, the skewness and kurtosis can be observed. The red line on the graph represents a normal distribution, which is very close as compared with the actual results of the histogram. Further details of the development of histograms are shown in Appendix G.1, where the effects of the number of simulations on the skewness and kurtosis of the distribution could be observed.

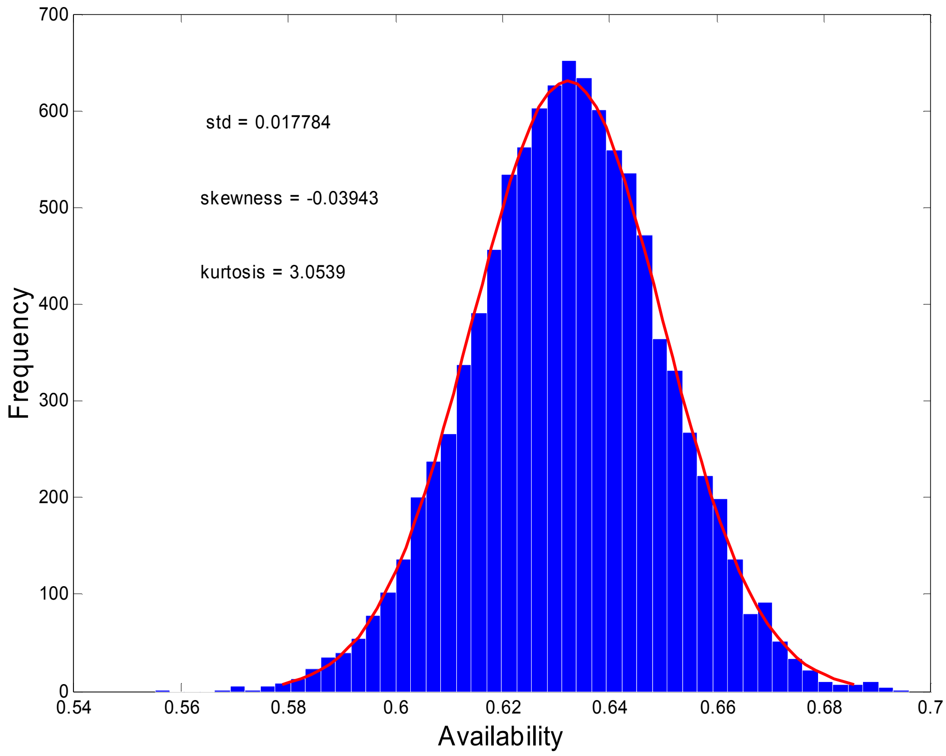

Figure 5.7 An example of a histogram of the availability of the baseline offshore wind farm for 100,000 simulations for MTTF of 0.5, with indications of the mean value, the standard deviation, skewness and kurtosis.

5.3.4 The effect of the capacity factor

Considering a planned intervention maintenance policy with two scheduled maintenance periods per year for the baseline offshore wind farm, i.e. London Array, the effect of different wind farm capacity factors can now be investigated using the model. Figure 5.8 shows the mean availability of the offshore wind farm, the cumulative energy output and LPC of energy by using 5 different capacity factors:

- 18%, (black) which represents the typical onshore wind farm minimum value,[7,30]

- 28%, (purple) which represents the typical onshore wind farm maximum value,[7,30]
- 34.2%, (green) which is the average value for the existing offshore wind farms (see Appendix D),
- 45%, (blue) which is the expected value for far offshore wind farms and
- 100%, (red) this value does not reflect reality because the wind can not be constantly feeding the wind turbines at the same speed and at the same rate for 100% of the time. But this value was chosen to show how the model reacts to extreme boundary values.

A number of important conclusions can be drawn from the results in Figure 5.8 on the effect of the capacity factor on the offshore wind farm:

- Considering the mean wind farm availability by varying the capacity factor in Figure 5.8, it can be observed that there is no variation by changing the value of the capacity factor, since there is no relationship between the capacity factor and wind farm availability.

- Considering the cumulative energy output by varying the capacity factor in Figure 5.8, it can be observed that as the capacity factor increases the energy output also increases, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4 (p. 110). What is interesting to observe in these curves is that as the capacity factor increases the difference in energy output between the curves also increases, which indicates that as the wind turbines become more reliable then the energy harness tends to significantly increase.

- Considering the LPC of energy by varying the capacity factor in Figure 5.8, it can be observed that the LPC of energy decreases as the capacity factor increases, this being explained by the increase in energy output as detailed in the previous paragraph.

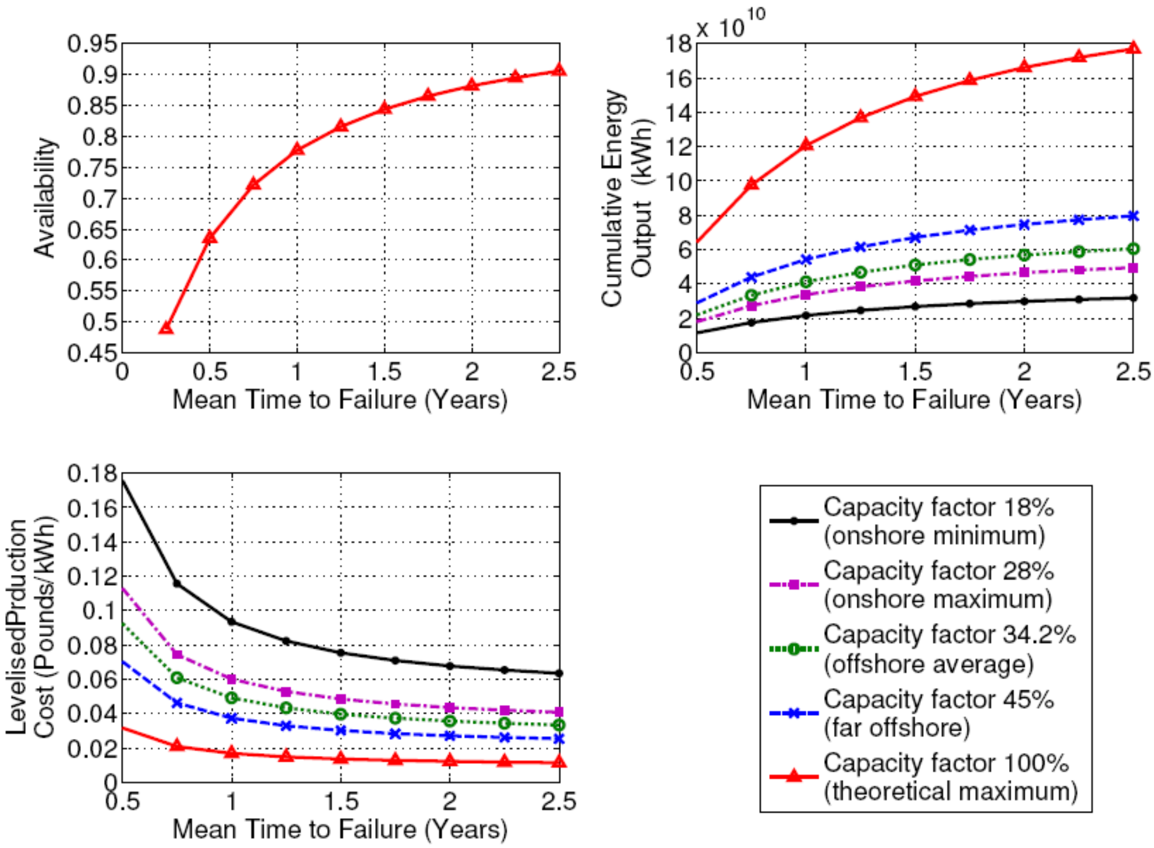

Figure 5.8 The effect of capacity factor on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.5 The effect of the number of wind turbines

Figure 5.9 shows the effect of varying the number of wind turbines within the baseline offshore wind farm. Three different wind turbine numbers have been used for the simulations, 100, 150 and 200, to show their effect on the mean wind farm availability, the cumulative energy output and LPC of energy:

- Considering the mean wind farm availability by varying the number of wind turbines in Figure 5.9, it can be observed that there is no variation by changing the number of wind turbines. This was anticipated because there is no relation between the capacity factor and wind farm availability. This can be true when assuming that the other input parameters of the baseline offshore wind farm are kept constant.

- Considering the cumulative energy output by varying the number of wind turbines in Figure 5.9, it can be observed that the cumulative energy output increases as the number of wind turbines in the offshore wind farm increase, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4. What is interesting to observe in these curves is that as the number of wind turbines increases the difference in energy output between the curves also increases, which indicates that as the wind turbines become more reliable then the energy harness tends to significantly increase. Considering that the wind turbine MTTF tends to 0.25 years then the energy output for different wind turbine numbers tends to significantly minimise, this being explained by the fact that the offshore wind turbines are failing so often that two scheduled maintenance visits per year are not enough to maintain high wind farm availability levels.

- Considering the LPC of energy by varying the number of wind turbines in Figure 5.9, it can be observed that the LPC of energy is presented in two different graphs. The two graphs show two different ranges of wind turbine MTTF on the x-axis $0.25<MTTF<0.5$ and $0.5<MTTF<2.5$. In both graphs, the LPC of energy decreases as the number of wind turbines in the offshore wind farm increase, as a result of higher energy output, this being expected from equation 4.8 previously presented for the economic model in Chapter 4 (p. 105).

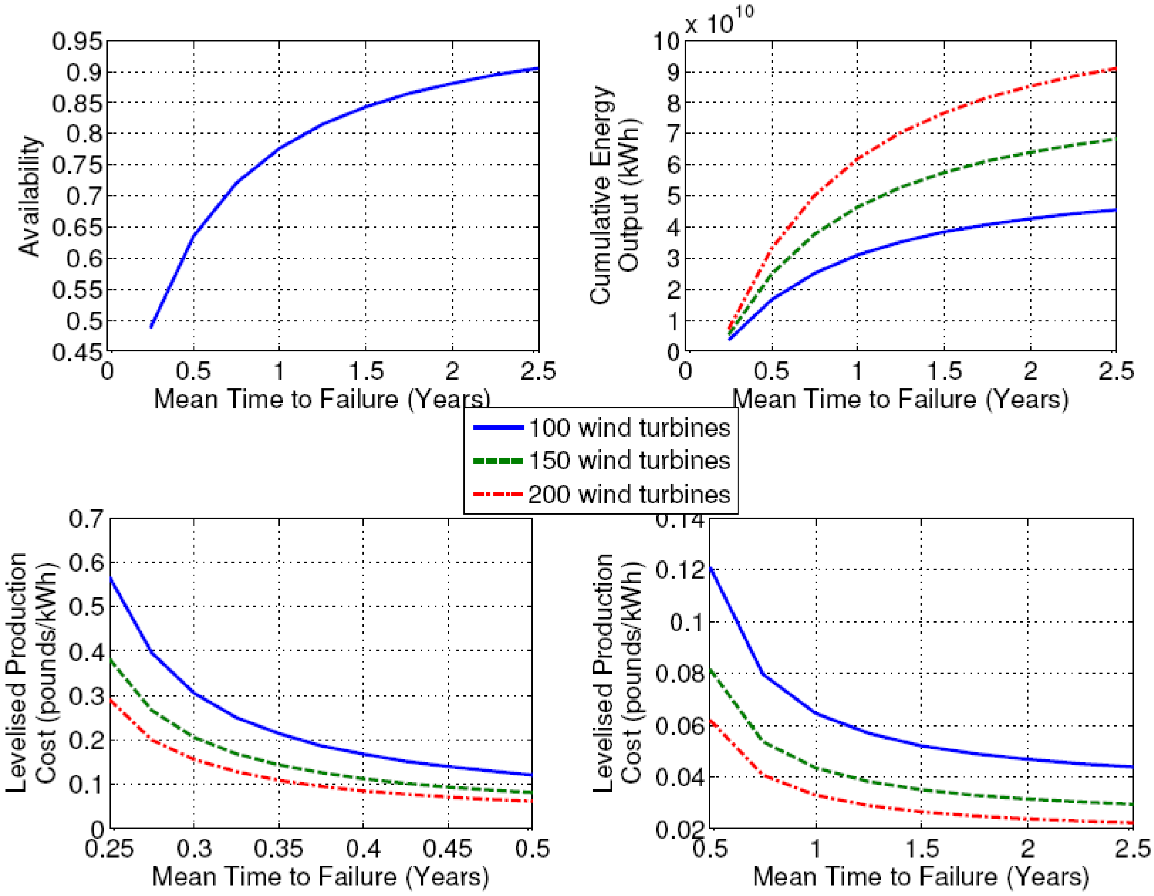

Figure 5.9 The effect of the number of wind turbines on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.6 The effect of the wind turbine power rating

Figure 5.10 shows the effect of varying the wind turbine power rating on the availability of offshore wind farm, cumulative energy output and LPC of energy. Three different wind turbine power ratings have been used for the simulations, 1, 2 and 5 MW representing the power rating of commercially available offshore wind turbines. There are a number of conclusions made on the results presented in Figure 5.10:

- Considering the mean wind farm availability by varying the wind turbine power rating in Figure 5.10, it can be observed that the mean wind farm availability is not affected by the change in the power rating of the wind turbines, since there is no relationship between the two offshore wind farm parameters.

- Considering the cumulative energy output by varying the wind turbine power rating in Figure 5.10, it can be observed that the cumulative energy output increases as the power rating of the wind turbine increase, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4 (p. 110). What is interesting to observe in these curves is that as wind turbine power rating increases the difference in energy output between the curves also increases, which indicates that as the wind turbines become more reliable then the energy harness tends to significantly increase. Considering that the wind turbine MTTF tends to 0.25 years then the energy output for different wind turbine numbers tends to significantly minimise, this being explained in the previous paragraph.

- Considering the LPC of energy by varying the wind turbine power rating in Figure 5.10, it can be observed that the LPC of energy is shown in two different graphs for two wind turbine MTTF ranges on the x-axis, $0.25<MTTF<0.5$ and $0.5<MTTF<2.5$. The LPC of energy decreases as the wind turbine power rating increases, as a result of higher energy harness, this being shown in equation 4.8 previously presented for the economic model in Chapter 4 (p. 105).

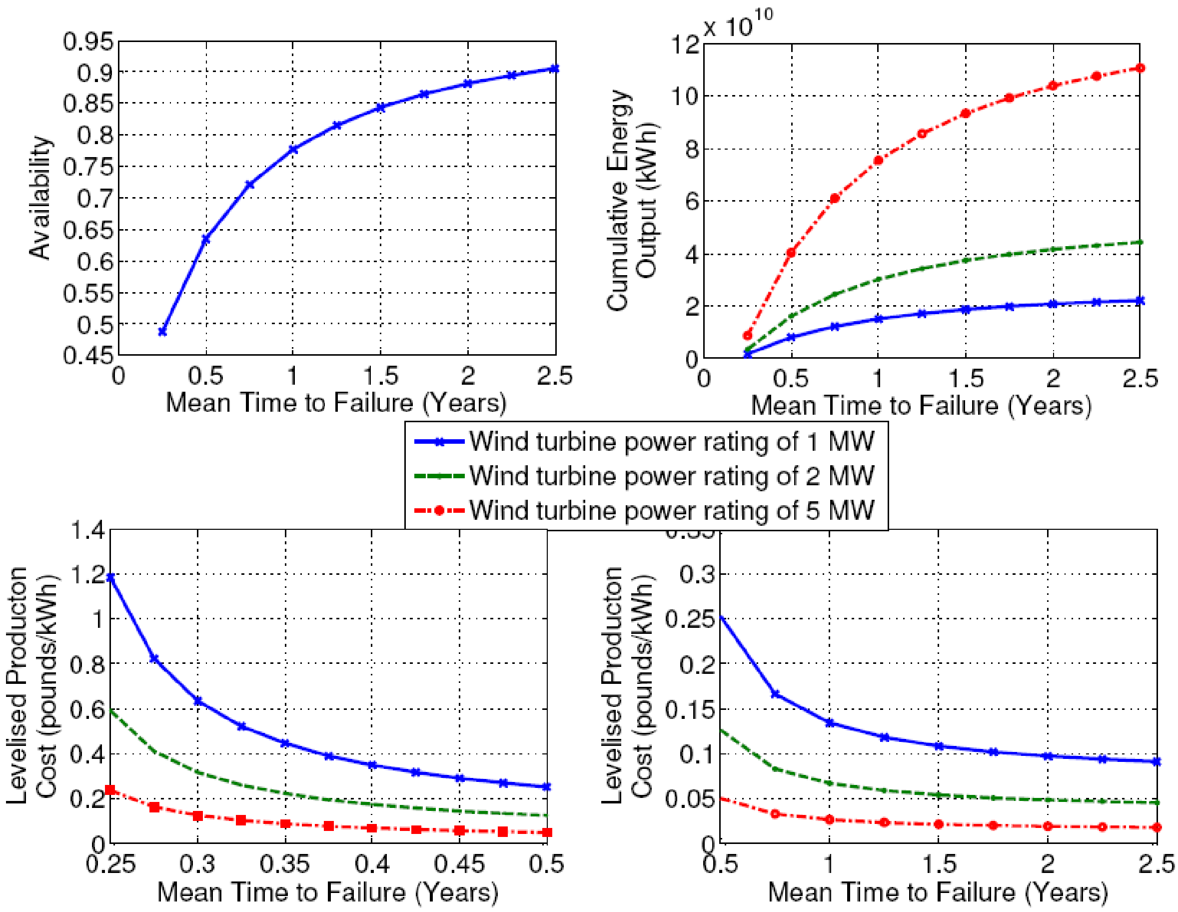

Figure 5.10 The effect of wind turbine power rating on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.7 The effect of the project duration

Figure 5.11 shows the effect of varying the total number of years of the offshore wind farm operation, on the availability of offshore wind farm, cumulative energy output and LPC of energy. Four different project duration values have been used, 5, 10, 20 and 30 years. There are a number of conclusions made on the results presented in Figure 5.11:

- Considering the mean wind farm availability by varying the number of wind farm operation years in Figure 5.11, it can be observed that the mean wind farm availability is not affected by the change the number of wind farm operation years, since there is no relationship between the two offshore wind farm parameters.

- Considering the cumulative energy output by varying the number of wind farm operation years in Figure 5.11, it can be observed that the cumulative energy output increases as the project duration increases, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4 (p. 110).

- Considering the LPC of energy by varying the wind farm operation years in Figure 5.11, it can be observed that the LPC of energy is shown in two different graphs for two wind turbine MTTF ranges on the x-axis, 0.25<MTTF<0.5 and 0.5<MTTF<2.5. The LPC decreases as the wind farm operation years increase, as a result of higher energy harness, this being shown in equation 4.8 previously presented for the economic model in Chapter 4 (p. 105). An interesting point to observe from the results obtained in Figure 5.11 is that the effect of varying the number of wind farm operation years on the LPC of energy decreases as wind turbine MTTF increases, this being explained by the fact that as the wind turbine becomes more reliable, i.e. increasing MTTF, then less failures would occur for the wind turbines and higher energy harness would be expected, as shown in Figure 5.11, and consequently lower LPC of energy would be achieved.

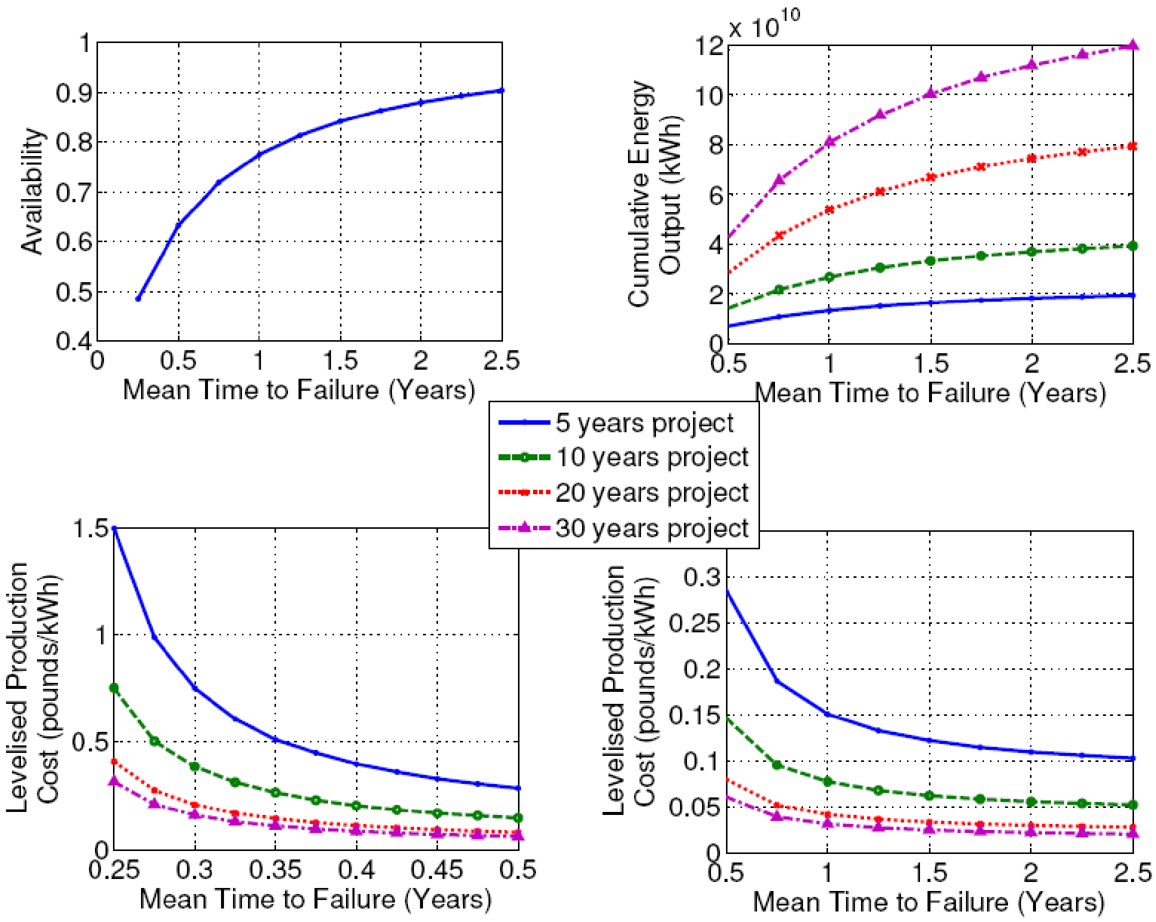

Figure 5.11 The effect of the number of project duration on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.8 The effect of the wind farm accessibility

Figure 5.12 shows the effect of varying the accessibility of the offshore wind farm on the availability of offshore wind farm, cumulative energy output and LPC of energy. Three different accessibility levels have been used for the simulations, which could result by unpredicted weather conditions and sea state during the scheduled maintenance period. For each scheduled maintenance visit to the offshore wind farm a random number of maintenance delay days has been simulated, using a mean for 10 and 20 days to simulate reduced accessibility levels and their effect on the output results, as shown in Figure 5.12. There are a number of conclusions made from the simulated results on Figure 5.12:

- Considering the mean wind farm availability by the wind farm accessibility in Figure 5.12, it can be observed that the mean wind farm availability decreases as the wind farm accessibility decreases, this being explained by equation 4.12 previously presented in the Monte Carlo model in Chapter 4 (p. 114).

- Considering the cumulative energy output by varying the wind farm accessibility in Figure 5.12, it can be observed that the cumulative energy output decreases as the wind farm accessibility decreases, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4 (p. 110).

- Considering the LPC of energy by varying the wind farm accessibility in Figure 5.12, it can be observed that the LPC of energy decreases as the wind farm accessibility increases, as a result of higher energy harness, this being shown in equation 4.8 previously presented for the economic model in Chapter 4 (p. 105). An interesting point to observe from the results obtained in Figure 5.12 is that the effect of varying the wind farm accessibility on the LPC of energy decreases as wind turbine MTTF increases, this being explained by the fact that as the wind turbine becomes more reliable, i.e. increasing MTTF, would mean less failures would occur for the wind turbines and higher energy harness would be expected, as shown in Figure 5.12, and consequently lower LPC of energy would be achieved.

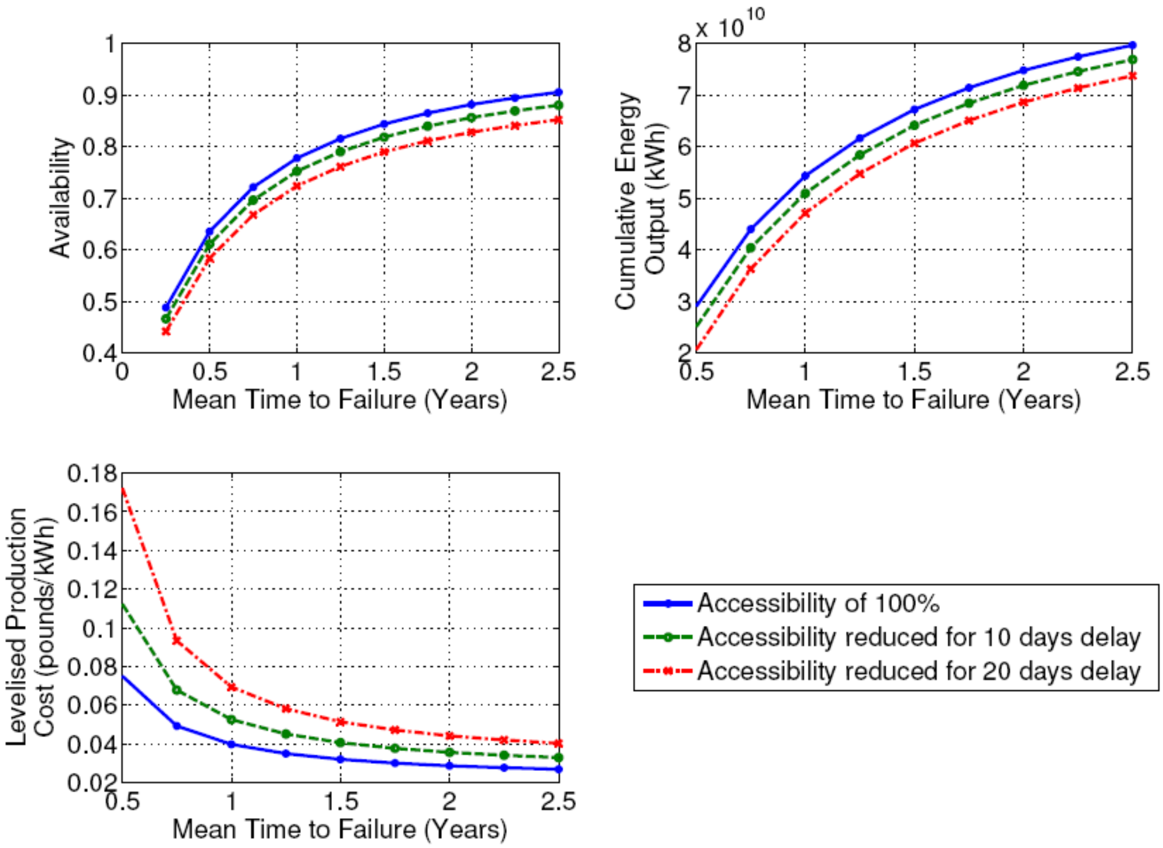

Figure 5.12 The effect of wind farm accessibility on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.9 The effect of the interest rate

Figure 5.13 shows the effect of varying the interest rate on the economical parameters of the offshore wind farm. Three different interest rate values 2%, 6% and 12% have been used to investigate how the wind farm availability, the cumulative energy output and LPC of energy are affected:

- Considering the mean wind farm availability by varying the interest rate in Figure 5.13, it can be observed that the mean wind farm availability is not affected by the change in the interest rate, since there is no relationship between the two offshore wind farm parameters.

- Similarly, considering the cumulative energy output by varying the interest rate in Figure 5.13, it can be observed that the energy output is not affected by the change in the interest rate, since there is no relationship between the two offshore wind farm parameters.

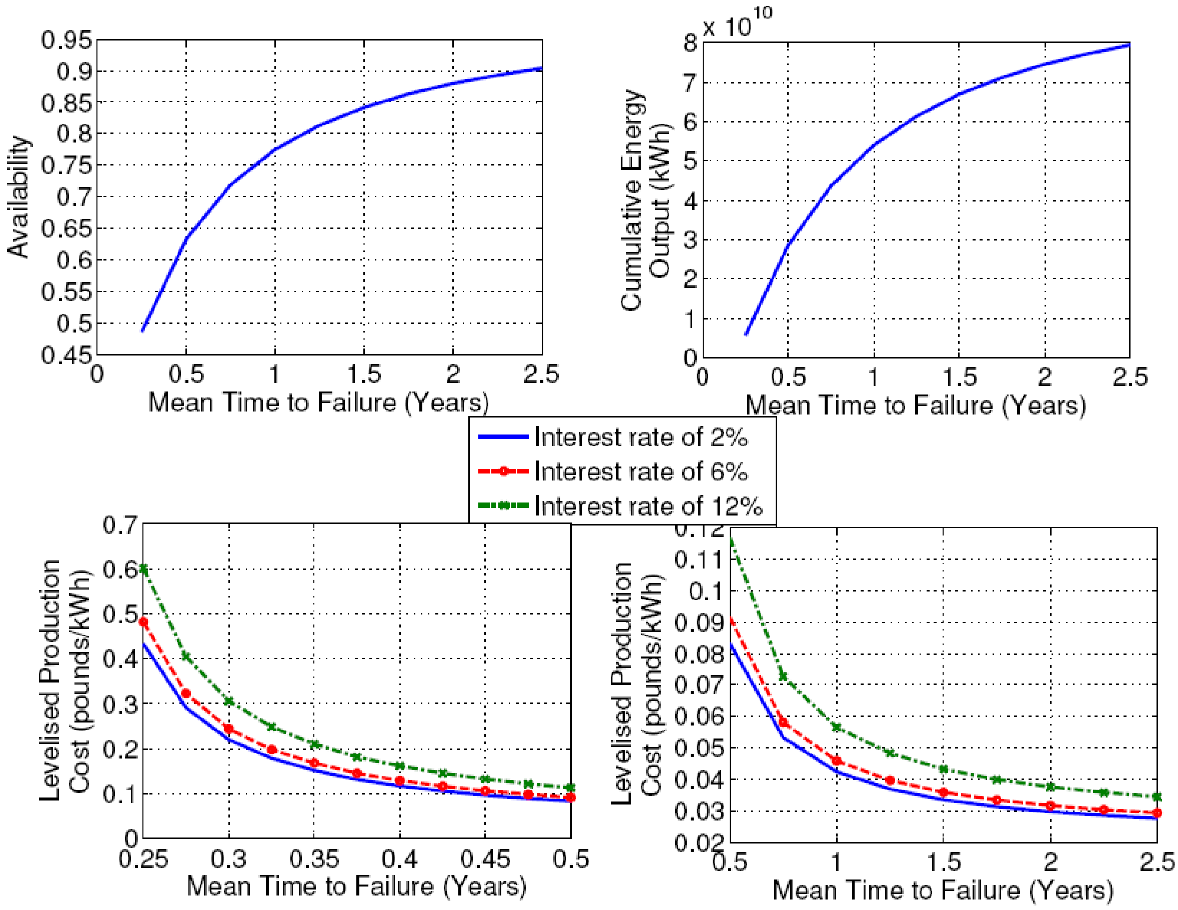

Figure 5.13 The effect of interest rate on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

- Considering the LPC of energy by varying the interest rate in Figure 5.13, it can be observed that the LPC of energy is shown in two different graphs for two wind turbine MTTF ranges on the x-axis, 0.25<MTTF<0.5 and 0.5<MTTF<2.5. The LPC of energy increases as the value of interest rate increases, as would be expected from equation 4.8 previously presented for the economic model in Chapter 4 (p. 105). An interesting point to observe from the results obtained in Figure 5.13 is that the effect of varying the interest rate on the LPC of energy decreases as wind turbine MTTF increases, this being explained by the fact that as the wind turbine becomes more reliable, i.e. increasing MTTF, then less failures would occur for the wind turbines and lower cost for the maintenance expeditions would be achieved, which in turn would result in lower LPC of energy.

5.3.10 The effect of the wind farm CAPEX

Figure 5.14 shows the effect of varying the CAPEX of the offshore wind farm on the availability of offshore wind farm, cumulative energy output and LPC of energy. Three different wind farm CAPEX values have been used for the investigation, which could result by a potential change in wind turbine purchase costs, installation costs, change in distance from shore and change in water depth. A 10% increase and 10% decrease of the actual CAPEX of the baseline offshore wind farm have been investigated. There are a number of conclusions made from the simulated results on Figure 5.14:

- Considering the mean wind farm availability by varying the CAPEX in Figure 5.14, it can be observed that the mean wind farm availability is not affected by the change in CAPEX, since there is no relationship between these two offshore wind farm parameters.

- Similarly, considering the cumulative energy output by varying the CAPEX in Figure 5.14, it can be observed that the energy output is not affected by the change in the CAPEX, since there is no relationship between the two offshore wind farm parameters.

- Considering the LPC of energy by varying the CAPEX in Figure 5.14, it can be observed that the LPC of energy is shown in two different graphs for two wind turbine MTTF ranges on the x-axis, $0.25<MTTF<0.5$ and $0.5<MTTF<2.5$. The LPC of energy increases as the value of CAPEX increases, as would be expected from equation 4.8 previously presented for the economic model in Chapter 4 (p. 105).

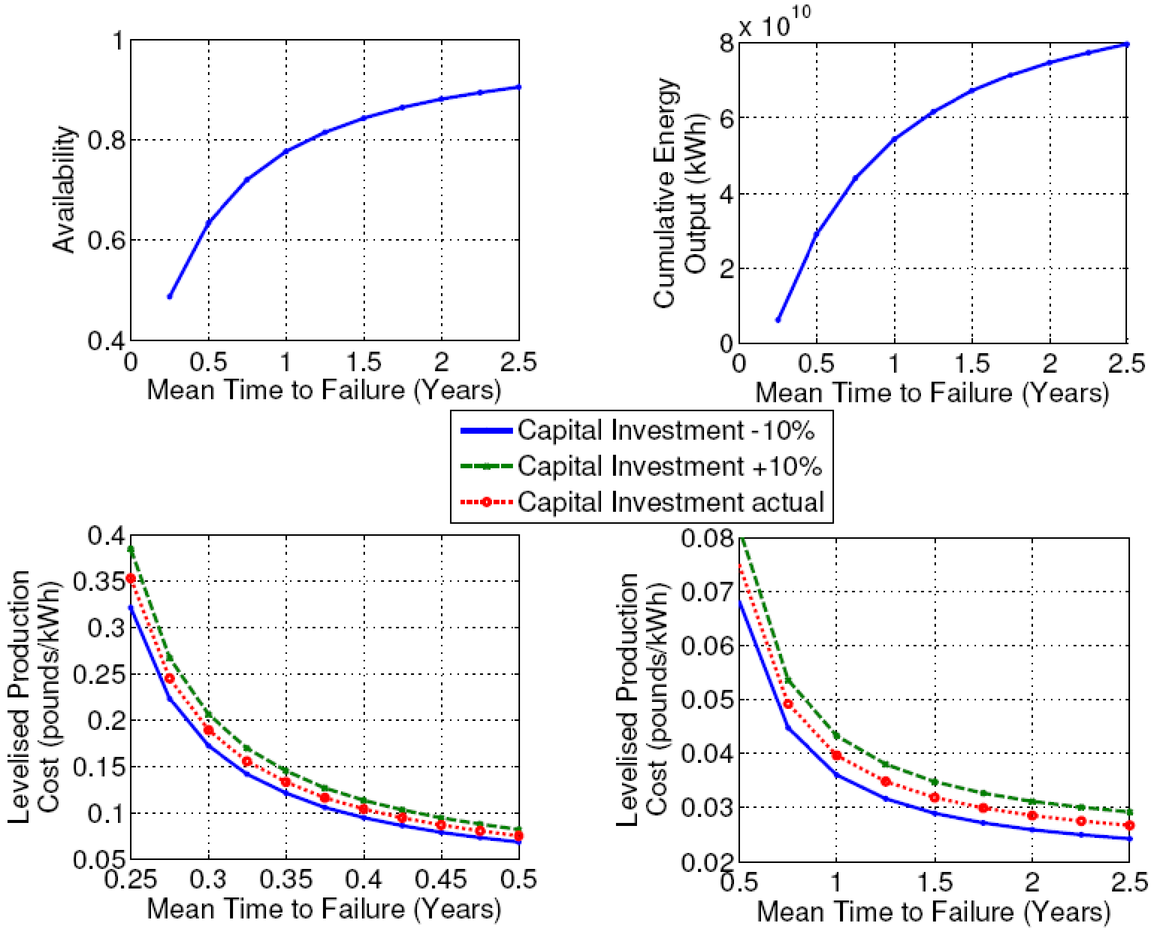

Figure 5.14 The effect of CAPEX on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.11 The effect of the decommissioning costs

Figure 5.15 shows the effect of varying the percentage of decommissioning costs of the offshore wind farm on the availability of offshore wind farm, cumulative energy output and LPC of energy. The decommissioning costs are simulated as a percentage of the CAPEX of the offshore wind farm, as previously explained for the economic model in Chapter 4. Four different decommissioning percentages have been investigated; 0% (actual), 2.5%, 5% and 10%. There are a number of conclusions made from the simulated results on Figure 5.15:

- Considering the mean wind farm availability by varying the decommissioning cost in Figure 5.15, it can be observed that the mean wind farm availability is not affected by the change in decommissioning cost, since there is no relationship between the two offshore wind farm parameters.

- Similarly, considering the cumulative energy output by varying the decommissioning cost in Figure 5.15, it can be observed that the energy output is not affected by the change in the decommissioning cost, since there is no relationship between the two offshore wind farm parameters.

- Considering the LPC of energy by varying the decommissioning cost in Figure 5.15, it can be observed that the LPC of energy is shown in two different graphs for two wind turbine MTTF ranges on the x-axis, $0.25<MTTF<0.5$ and $0.5<MTTF<2.5$. The LPC of energy increases as the value of decommissioning cost increases, as would be expected from equation 4.8 previously presented for the economic model in Chapter 4 (p. 105). However it can be observed on Figure 5.15 for the effect of the increase in decommissioning cost has a small effect on the LPC of energy, this being explained by the high CAPEX and the cost per installed wind turbine (11.2 million pounds) of the London Array offshore wind farm, whilst it is expected for the decommissioning cost to have a higher effect on the LPC of energy when considering lower CAPEX and cost of installed wind turbines for other offshore wind farms, which is investigated in detail in the following chapters.

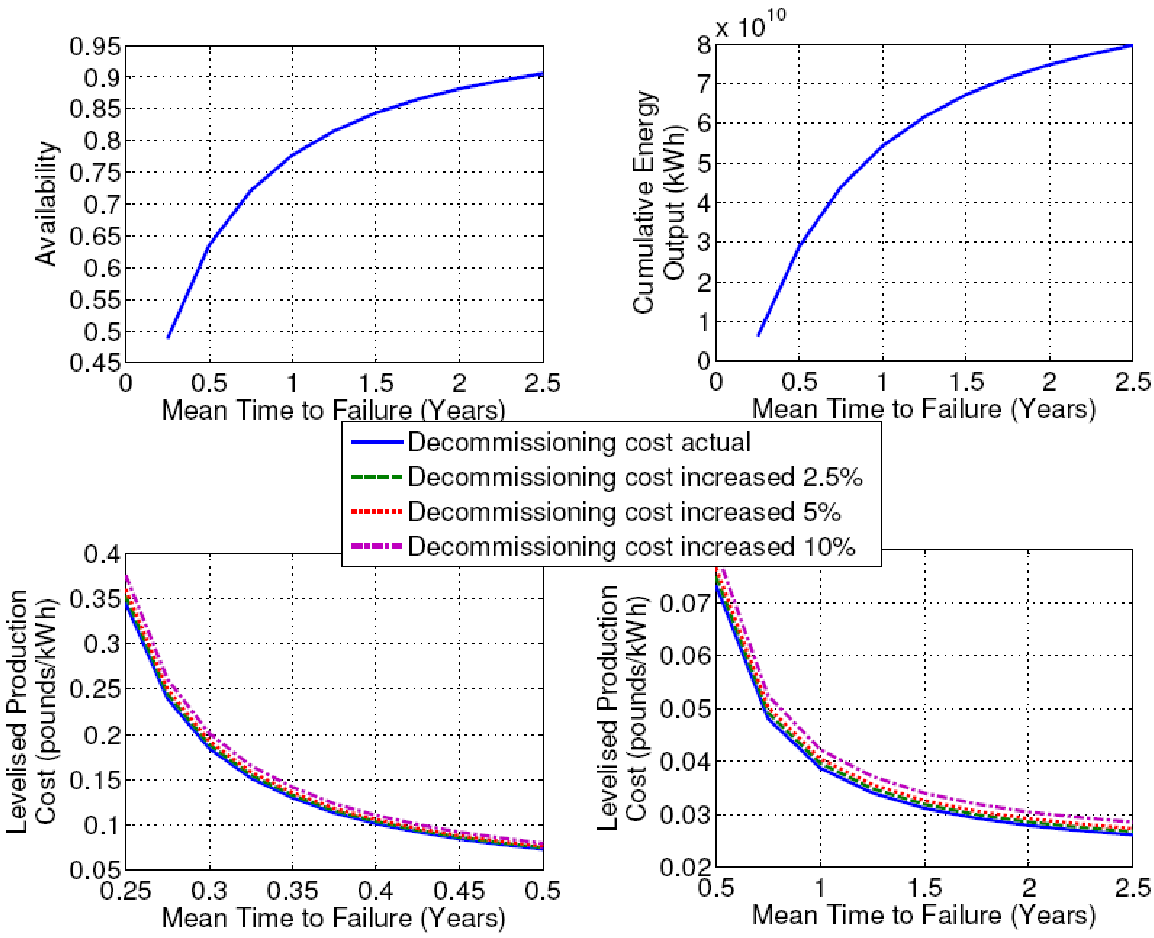

Figure 5.15 The effect of decommissioning costs on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.12 The effect of the transportation costs

Figure 5.16 shows the effect of varying the vessel hiring costs on the economical parameters of the offshore wind farm. Four different vessel hiring costs as a daily rate have been investigated; 15,000 pounds, 25,000 pounds, 50,000 pounds and 100,000 pounds, this being suggested by Hodges (2008)[67] for the near and far future offshore wind farm development as explained in the following paragraph.

It has been reported that there is a significant shortage of vessels that are used for the installation and repairs and maintenance of offshore wind farms.[66,67] This observation could potentially result in an increased market demand for these vessels, which increases their hiring costs. Considering the corrective maintenance strategy the maintenance expedition times are unpredictable in their majority, showing a greater dependency upon the availability of these vessels, whilst when considering a planned intervention maintenance policy, the repairs and maintenance of the wind turbines are well planned prior to the maintenance expeditions and the number or type of maintenance vessels and helicopters required are known in advanced, before the scheduled maintenance period commences, which could result in a lower dependency on the availability of hiring the vessels and potentially secure lower hiring price.

Figure 5.16 shows the effect of varying the maintenance vessel hiring cost for the wind farm availability and LPC of energy all plotted against wind turbine MTTF. Considering the wind farm availability against wind turbine MTTF then the wind farm availability is not affected by the change in transportation costs since there is no relationship between the two parameters. The same conclusion would be observed for the effect of varying the maintenance vessel hiring cost on the cumulative energy output since there is no relationship between the two parameters.

Now considering the LPC of energy against wind turbine MTTF for varying the maintenance vessel hiring cost it can be observed in Figure 5.16 that the LPC of energy is presented in two different graphs for two wind turbine MTTF ranges on the x-axis, 0.25<MTTF<0.5 and 0.5<MTTF<2.5. The LPC increases as the transportation costs increase, as would be expected from equation 4.8 previously presented for the economic model in Chapter 4 (p. 105).

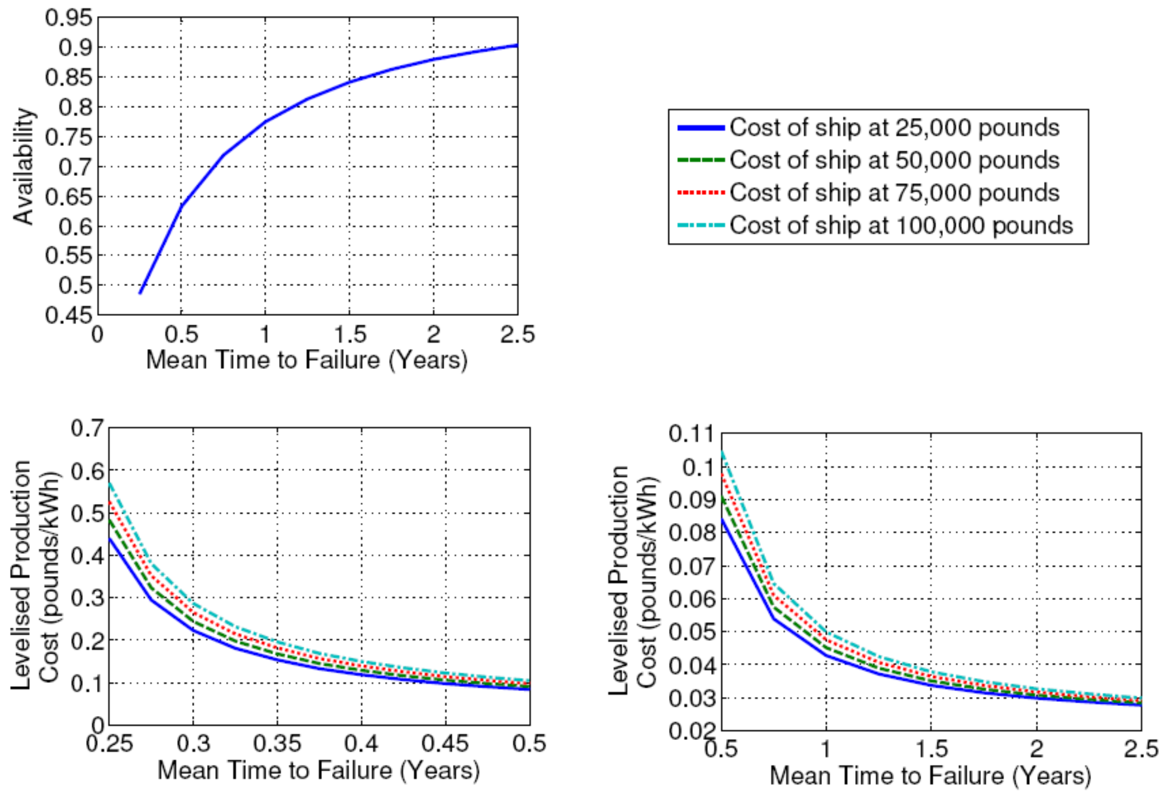

Figure 5.16 The effect of transportation costs on the mean availability, cumulative energy output and LPC for the baseline offshore wind farm with two planned intervention periods per year.

5.3.13 The effect of the distance to shore on the CO2 emissions

The calculation of the CO2 emissions for the transportation means (helicopters and vessels) is based on the kilometres travelled as detailed in Appendix I. Figure 5.17 shows the effect of varying the distance to shore of the offshore wind farms on the number of journeys by the vessels to the offshore wind farm, the total distance travelled by the vessels and the total CO2 emissions for the vessels all plotted against the wind turbine MTTF. Four different distances to shore have been investigated; 10 km, 46 km, 100 km, and 200 km. There are a number of conclusions made from the simulated results on Figure 5.17:

- Considering the number of vessel journeys to the offshore wind farm by varying the distance to shore in Figure 5.17, it can be observed that the number of vessel journeys is not affected by the change of the distance to shore, which indicates that there is no dependency between the two parameters, as would be expected from the equation presented in Appendix I. The number of vessel journeys to the offshore wind farm decreases for increasing wind turbine MTTF, as would be expected, this being explained because the number of vessel journeys to the offshore wind farm represents the number of wind turbine failures. The curve on Figure 5.16 between the number of vessel journeys and the wind turbine MTTF is of a hyperbolic nature (rectangular hyperbola), this being explained because the relationship between the number of wind turbine failures has a linear relationship with the MTTR of the wind turbines, which in turn is inversed proportional to the wind farm availability as shown in equation 4.12 previously presented in the Monte Carlo model in Chapter 4 (p. 114). Consequently, the curve between number of vessel journeys and the wind turbine MTTF is of a hyperbolic nature.

- Considering the total distance travelled by vessels when varying the distance to shore in Figure 5.17, it can be observed that the total distance travelled by the vessels decreases as the wind turbine MTTF increases, as a result of the decrease in the number of vessel journeys for increasing wind turbine MTTF. The total distance travelled by the vessels against wind turbine MTTF is a curve of hyperbolic nature (rectangular hyperbola), since the relationship between the total distance travelled and the number of vessel journeys to the offshore wind farm is linear, consequently, the curve relationship between wind turbine MTTF and total distance to shore also becomes inversed proportional. The total distance travelled by the vessels increases with increasing distance to shore, as would be expected from the equations presented in Appendix I.

- Considering the total CO2 emissions from vessels when varying the distance to shore in Figure 5.17, it can be observed that the total CO2 emissions from vessels decreases as the wind turbine MTTF increases, as a result of the decrease in the number of vessel journeys to the offshore wind farm for increasing wind turbine MTTF. The total CO2 emissions from vessels increases with increasing distance to shore, as would be expected from the equations presented in Appendix I.

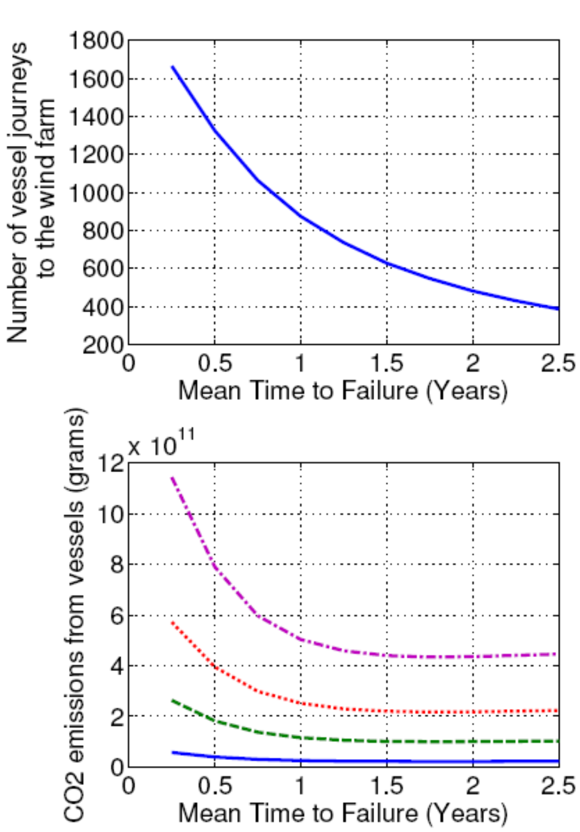

Figure 5.17 The effect of wind farm distance to shore on the number of vessel journeys and CO2 emissions for the baseline offshore wind farm with two planned intervention periods per year

5.3.14 The effect of the transportation CO2 emissions

Figure 5.18 shows the effect of varying the transportation CO2 emissions per kilometre travelled on the number of journeys by the vessels to the offshore wind farm, the total distance travelled by the vessels and the total CO2 emissions for the vessels all plotted against the wind turbine MTTF. Three different values for the vessels CO2 emissions per kilometre travelled have been investigated; 50,000 grams/km, 120,000 grams/km and 200,000 grams/km. There are a number of conclusions made from the simulated results on Figure 5.18:

- Considering the number of vessel journeys to the offshore wind farm when varying the vessel CO2 emissions on a kilometre basis in Figure 5.18, it can be observed that the number of vessel journeys to the offshore wind farm are not affected by the change in the vessel CO2 emissions on a kilometre basis, which indicates that there is no dependency between the parameters, as expected from the equations presented in Appendix I.

- Similarly, considering the distance travelled by the vessels when varying the vessel CO2 emissions on a kilometre basis in Figure 5.18, it can be observed that the distance travelled by the vessels is not affected by the change in the vessel CO2 emissions on a kilometre basis, which indicates that there is no dependency between the parameters, as expected from the equations presented in Appendix I.

- Considering the total CO2 emissions from vessels when varying the vessel CO2 emissions on a kilometre basis in Figure 5.18, it can be observed that the total CO2 emissions from vessels decreases as the wind turbine MTTF increases, as a result of the decrease in the number of vessel journeys for increasing wind turbine MTTF. The total CO2 emissions from vessels increases with increasing vessel CO2 emissions, as would be expected from the equations presented in Appendix I.

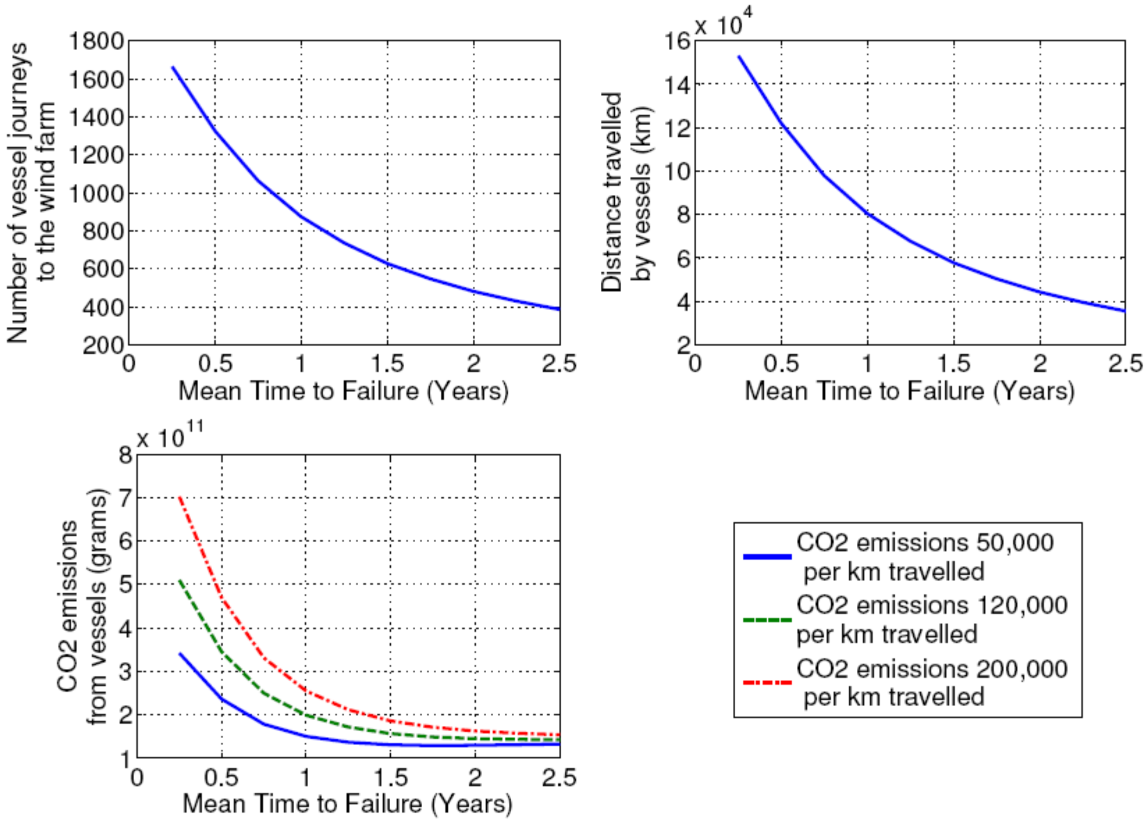

Figure 5.18 The effect of transportation emissions on the number of vessel journeys and CO2 emissions for the baseline offshore wind farm with two planned intervention periods per year

5.4 Conclusions

The validation of the computer simulation programs for the planned intervention maintenance policy has been performed in this Chapter by comparing the results obtained from the developed model against published data in available literature. The comparison between the results obtained from the simulations and the published data show a consistency between the different planned intervention maintenance policy scenarios investigated and are directly comparable against the results obtained from the corrective maintenance strategy, as obtained from the published projects, i.e. Opti-Owecs and DOWEC.

A baseline offshore wind farm has been established in this Chapter in order to conduct a sensitivity analysis on the input parameters of the developed model, in order to give added confidence in the structure of the computer simulation programs. The sensitivity analysis has shown that the models developed react to different input parameters as would be expected when considering the background theory explained in Chapters 3 and 4.

The developed computer simulations programs can now be used in the following Chapter on existing and future offshore wind farm case studies in order to produce results for the planned intervention maintenance policy to investigate the applicability of the proposed maintenance strategy.

6 Case Studies and Model Results

6.1 Introduction

In this chapter a number of case studies are considered for the application of the planned intervention maintenance policy, using the ‘PM 1’ and ‘PM 2’ scenarios. The case studies are the London Array offshore wind farm, which formed the baseline study in the previous chapter, the Beatrice offshore wind farm project, which is a state of the art, small wind farm using prototype 5 MW wind turbines, and the Kentish Flats offshore wind farm, which represents an operational medium size project. For each of the case studies investigations were carried out to determine the benefits and drawbacks of the planned intervention maintenance policy with variations in the key input parameters and variables. Results are presented in graphical form and discussed in detail and conclusions reached as to the viability of planned intervention maintenance policy.

A further area of investigation reported in this chapter is the CO2 emissions from the maintenance transportation systems, i.e. vessels and helicopters, when undertaking maintenance, with the reactive response being compared to the planned intervention maintenance policy. This investigation involved the development of the corrective maintenance strategy model to simulate CO2 emissions.

6.2 Case Study 1 – London Array offshore wind farm

The London Array offshore wind farm is a large offshore wind farm located far from shore. Table 6.1 shows the input parameters of the London Array offshore wind farm, which were used to determine mean wind farm availability, cumulative energy output and LPC of energy.

Table 6.1 London Array offshore wind farm parameters.[92]

Parameters	Value
Turbine Power rating	3.6 MW (Siemens)
Number of Turbines	175
Distance to shore	46 km
Annual interest rate	5%
Economic lifetime of project	20 years
Capacity factor	45%
Cost of maintenance vessel (cranes)	25,000 pounds (daily rate)
Cost of helicopters or small vessels	5,000 pounds (daily rate)
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Decommissioning	2.5% of capital investment cost
Capital Investment cost	1.96 billion pounds

Figure 6.1 shows a comparison between the 'PM 1' (blue) and PM 2' (green) scenarios of the planned intervention maintenance policy for the London Array offshore wind farm, whereby the outputs are presented in terms of wind farm availability,

cumulative energy output and LPC of energy, which have been plotted against wind turbine MTTF.

Considering wind farm availability versus the wind turbine MTTF in Figure 6.1 then the two curves representing the ‘PM 1’ and ‘PM 2’ scenarios show how the wind farm availability increases with increasing wind turbine MTTF, as would be expected. The ‘PM 2’ scenario yields higher availability levels when compared to the ‘PM 1’ scenario, this being explained by the fact that ‘PM 2’ scenario has twice as many scheduled maintenance visits to the offshore wind farm each year. As the wind turbine MTTF increases the difference in wind farm availability as shown by the two curves, decreases, which indicates that as the wind turbines become more reliable the difference between the two scenarios tends to minimise, as would be expected.

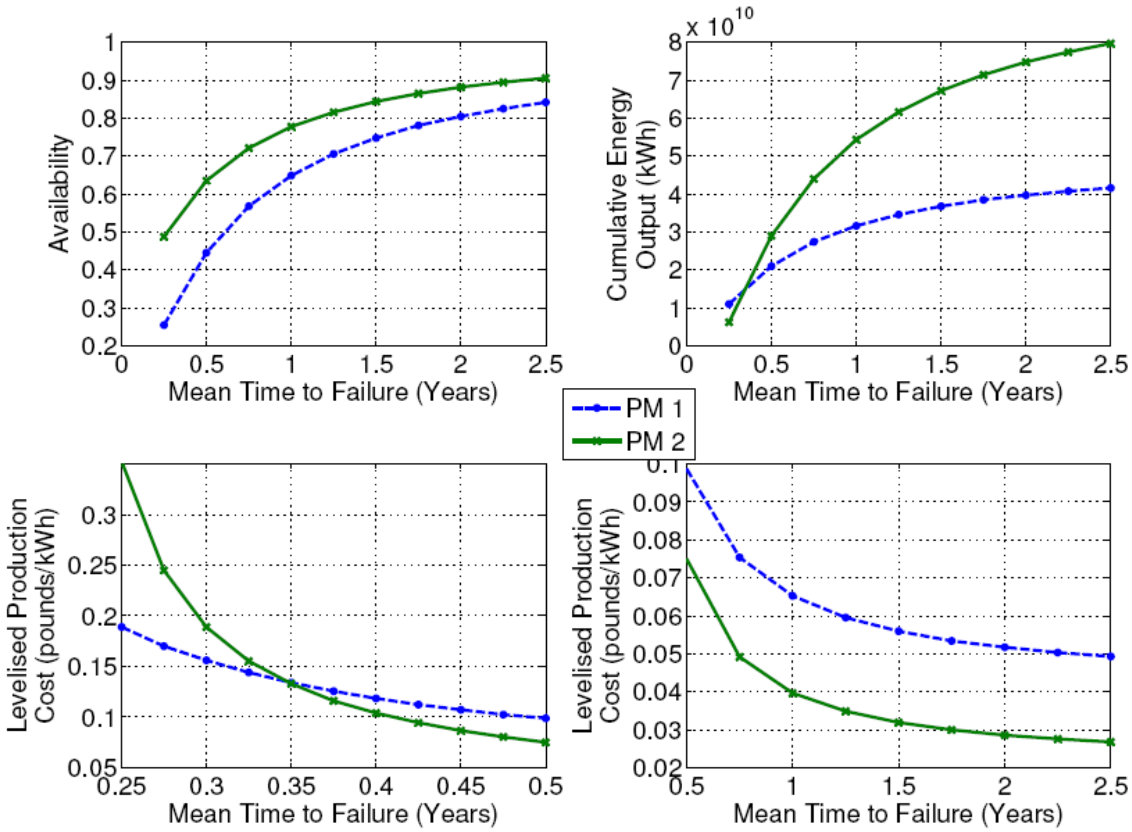

Figure 6.1 The comparison between the planned intervention maintenance policy scenarios, PM1 and PM2, for the London Array offshore wind farm, in terms of wind farm availability, cumulative energy output and LPC of energy

Now consider the energy output versus wind turbine MTTF in Figure 6.1. The 'PM 2' curve intersects the 'PM 1' curve at a wind turbine MTTF of 0.33 years. For wind turbine MTTF levels lower than 0.33 years the 'PM 1' scenario yields higher energy output compared to the 'PM 2' scenario, whilst for wind turbine MTTF levels higher than 0.33 years the 'PM 2' scenario yields higher energy output. This may be explained by considering the energy losses during the scheduled maintenance periods. For the 'PM 1' scenario the scheduled maintenance visits are planned during July where the energy losses for repairs and preventive maintenance would account for a maximum of 5.8% of the total energy output over the operational year, as discussed earlier when explaining the energy model in Chapter 4 (p. 110). For the 'PM 2' scenario the scheduled maintenance visits are planned twice a year, during October and May, where the energy losses for repairs and preventive maintenance would account for a maximum of 15.9% (8.8% for October and 7.1% for May) of the total energy output for the operational year, also explained earlier in Chapter 4 (p. 111). The above observation indicates that the energy losses incurred for the 'PM 2' scenario as the wind turbine MTTF tends to 0.25 years would increase significantly, as compared to the energy loss for the 'PM 1' scenario.

It should also be considered that the proactive nature of the planned intervention maintenance policy, as previously explained in Chapter 3, would require preventive maintenance tasks to take place on all the wind turbines, which in turn results in the wind turbines stopping for the maintenance work to take place. This practice, which is identified in Chapter 3 (p. 73-78) as a main disadvantage of planned intervention maintenance policy, is performed twice as many times for the 'PM 2' scenario, which in turn results in even higher energy loss, as compared to 'PM 1' scenario.

Now consider the LPC of energy versus the wind turbine MTTF in Figure 6.1, which is presented in two different graphs for two wind turbine MTTF ranges, i.e. $0.25 \leq MTTF \leq 0.5$ and $0.5 \leq MTTF \leq 2.5$. Considering the LPC of energy for $0.25 \leq MTTF \leq 0.5$, the 'PM 1' curve intersect the 'PM 2' curve at a wind turbine MTTF of 0.35 years. For wind turbine MTTF levels lower than 0.35 years the 'PM 1' scenario yields lower LPC of energy compared to the 'PM 2' scenario, whilst for wind turbine MTTF levels higher than 0.35 years the 'PM 2' scenario yields lower LPC of energy, this being a result of the energy output change discussed in the previous paragraph, since the LPC of energy and the energy output are inversely proportional, as discussed earlier in Chapter 4 (p. 105 - 110). Considering the LPC of energy for 0.5≤MTTF≤2.5 then the curve for 'PM 2' shows significantly lower results as compared to the 'PM 1' curve, this being explained by the higher energy output as the wind turbine MTTF increases. This observation indicates that as the wind turbine reliability increases then the 'PM 2' scenario would be preferred over the 'PM 1' scenario.

6.2.1 The effect of the mean time to repair

Figure 6.2 shows the effect of varying the wind turbine mttr (mean time to repair) and mtpm (mean time for preventive maintenance), on the cumulative energy output and LPC of energy, plotted against wind turbine MTTF, for comparing the planned intervention maintenance scenarios, 'PM 1' (blue) and 'PM 2' (green). The change in wind turbine mttr and mtpm could result from a change in lead time for spare parts, availability of transportation means and sudden change in weather conditions which could affect the accessibility to the wind turbines, therefore these effects are examined in Figure 6.2. This figure was constructed to investigate how the intersection point between the two curves, i.e. 'PM 1' and 'PM 2', changes by varying the wind turbine mttr and mtpm, as being a significant conclusion of the results in Figure 6.1. The four graphs in Figure 6.2 are divided into two sections; the left section consisting of two graphs for the 'low mttr' simulations, and the right sections also consisting of two graphs for the 'high mttr' simulations. Two different values for the wind turbine mttr and mtpm have been investigated; 'low mttr', which simulates half the input parameter values of mttr and mtpm, i.e. mttr=0.75 days and mtpm=0.5 days (left section graphs), and 'high mttr', which simulates two fold the input parameter values of mttr and mtpm, i.e. mttr=3 days and mtpm=2 days (right section graphs).

Considering the energy output versus the wind turbine MTTF (upper graphs) in Figure 6.2, it can be observed that for the 'low mttr' graph, the intersection point between the 'PM 1' and 'PM 2' curves reduces to a wind turbine MTTF of 0.32 years, as compared to the results shown in Figure 6.1, whilst for the 'high mttr' graph, the intersection point between the 'PM 1' and 'PM 2' curves increases to wind turbine MTTF of 0.34 years, as compared to the results shown in Figure 6.1. These results indicate that as the repair time of the wind turbines increases then the 'PM 1' scenario yields higher energy output for a larger wind turbine MTTF range, as compared to the 'PM 2' scenario.

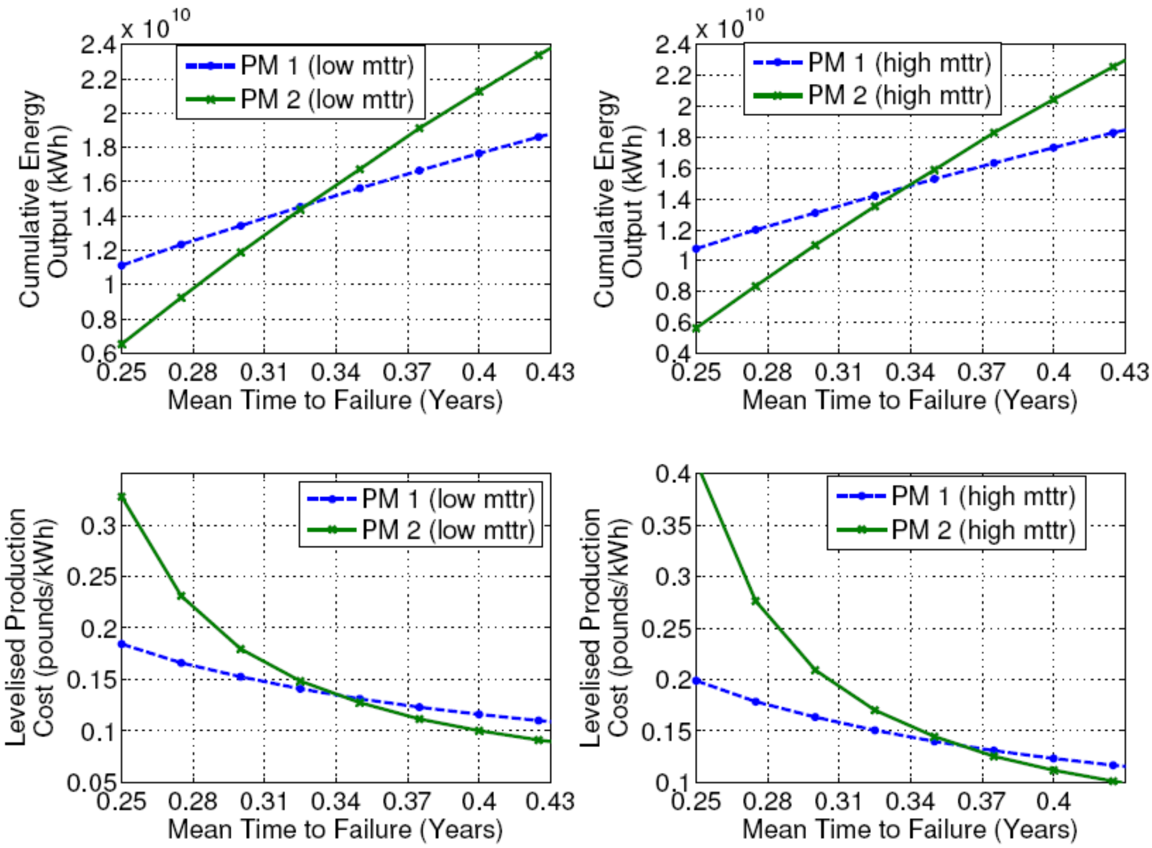

Figure 6.2 The effect of mttr and mtpm on the cumulative energy output and LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2.

Now consider the LPC of energy versus the wind turbine MTTF (lower graphs) in Figure 6.2, it can be observed that for the 'low mttr' graph, the intersection point between the ‘PM 1’ and ‘PM 2’ curves reduces to wind turbine MTTF of 0.34 years, whilst for the ‘high mttr’ graph, the intersection point between the ‘PM 1’ and ‘PM 2’ curves increases to wind turbine MTTF of 0.36 years, as compared to the results shown in Figure 6.1. These results indicate that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, as compared to the ‘PM 2’ scenario, and would therefore be preferred over the ‘PM 2 scenario.

6.2.2 The effect of the capacity factor

Figure 6.3 shows the effect of varying the capacity factor of the London Array offshore wind farm, which could result from the change in wind farm location or a change in the wind strength at the wind farm. Two different capacity factors have been used, i.e. 35% and 55% (which represent a feasible range for offshore wind farms), to produce results in terms of cumulative energy output and LPC of energy, all plotted against wind turbine MTTF. The six graphs in Figure 6.3 compare the ‘PM 1’ (blue) and ‘PM 2’ (green) scenarios of the planned intervention maintenance policy. The graphs in Figure 6.3 have been divided into two sections with a dividing line between them. The left section, consisting of three graphs, presents the results for a capacity factor of 35% and the right section presents the results of a capacity factor of 55%. The axes on the related graphs have been set to have the same limits to assist the comparison between the two sections.

Considering the energy output versus the wind turbine MTTF (two upper graphs), it can be observed that the ‘PM 2’ scenario achieves higher energy output for both the capacity factors that have been simulated, as compared to ‘PM 1’ scenario, this being explained by the fact that ‘PM 2’ scenario has twice as many scheduled maintenance visits to the offshore wind farm each year. What is interesting to observe in these graphs is that as the capacity factor increases the difference in energy output between the two curves also increases, which indicates that for wind turbine MTTF>0.35, as the capacity factor increases the 'PM 2' scenario would be preferred, over the 'PM 1' scenario.

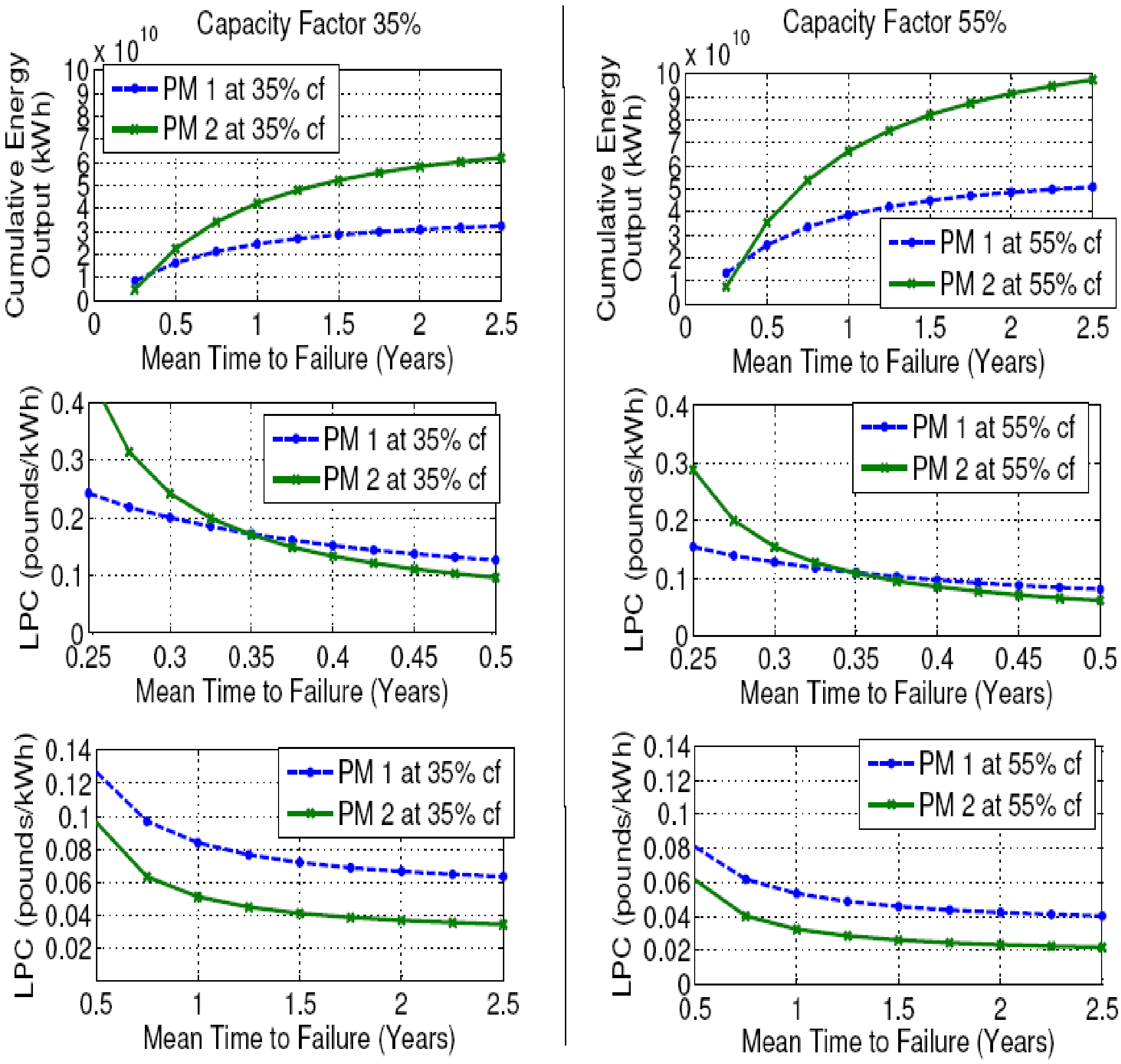

Figure 6.3 The effect of the capacity factor on the cumulative energy output and LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the London Array offshore wind farm

Now consider the LPC of energy versus the wind turbine MTTF (four lower graphs). Two different wind turbine MTTF ranges have been used to present the comparison between the 'PM 1' and 'PM 2' scenarios, i.e. 0.25≤MTTF≤0.5 and 0.5≤MTTF≤2.5. Considering the LPC of energy for 0.25≤MTTF≤0.5 (two middle graphs), the 'PM 1' curve intersects the 'PM 2' curve at lower value of LPC of energy (0.1 £/kWh) for a capacity factor of 55%, as compared to a capacity factor of 35% (0.18 £/kWh), which indicates that for 0.25≤MTTF≤0.5, as the capacity factor increases the difference in LPC of energy between the ‘PM 1’ and ‘PM 2’ curves decreases. Considering the LPC of energy for 0.5≤MTTF≤2.5 (two lower graphs), the comparison between the two scenarios indicates that the difference in LPC of energy between the two curves also decreases when the capacity factor of the wind farm increases. The significant point when observing the results simulated for Figure 6.3 is that as the capacity factor increases the ‘PM 2’ scenario tends to increase the preference over the ‘PM 1’ scenario, because it achieves higher energy output and lower LPC of energy.

6.2.3 The effect of the transportation costs

Figure 6.4 shows the effect of varying the cost of transportation means on the LPC of energy, plotted against wind turbine MTTF, for comparing the planned intervention maintenance scenarios, ‘PM 1’ (blue) curve and ‘PM 2’ (green) curve. This figure was constructed to investigate how the intersection point between the two curves changes by varying the cost of transportation means. The variation in the hiring cost of maintenance vessels is associated with the availability of the vessels, i.e. as the demand in maintenance vessels increases and their supply remains constant, then their hiring cost will increase, as has been suggested by Hodges (2008)[67]. Two different input parameter values for the cost of maintenance vessels have been investigated; 10,000 and 100,000 pounds as a daily rate for hiring the vessels.

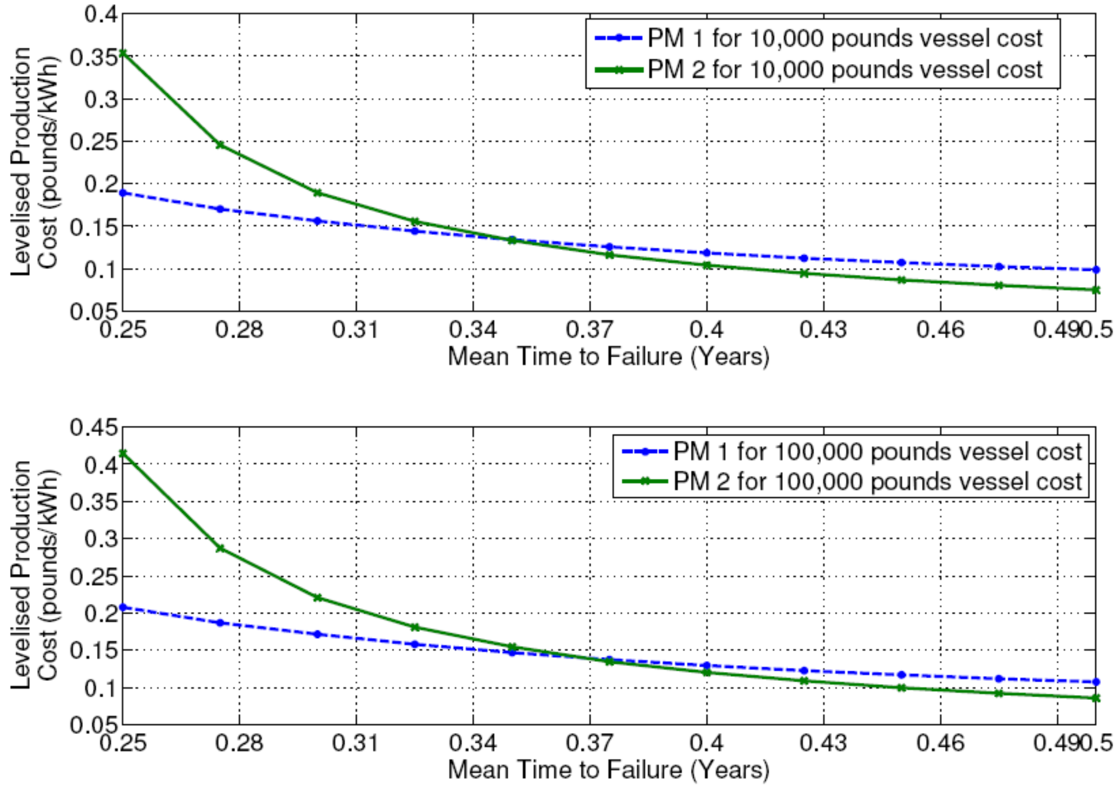

Figure 6.4 The effect of the cost of transportation means on the LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the London Array offshore wind farm

Considering the LPC of energy versus the wind turbine MTTF for vessel hiring costs of 10,000 pounds then it can be observed that the intersection point between the ‘PM 1’ and ‘PM 2’ curves also reduces to wind turbine MTTF of 0.345 years, as compared to the results presented in Figure 6.1, whilst by increasing the cost of vessel hiring to 100,000 pounds, then the intersection point of the of the ‘PM 1’ and ‘PM 2’ curves also increases to give a wind turbine MTTF of 0.37 years. An interesting point that these results indicate is that as the cost of maintenance vessels increases then the ‘PM 1’ scenario yields lower LPC of energy and consequently would be preferred over the ‘PM 2’ scenario, for a larger wind turbine MTTF range.

6.2.4 The effect of the number of failures

Figure 6.5 shows the comparison between the ‘PM 1’ (blue) and PM 2’ (green) scenarios of planned intervention maintenance policy for the London Array offshore wind farm, where the outputs are presented in terms of the number of wind turbine failures, total cost of maintenance, percentage of maintenance cost in LPC of energy, and percentage of maintenance costs in CAPEX, which have been plotted against wind turbine MTTF.

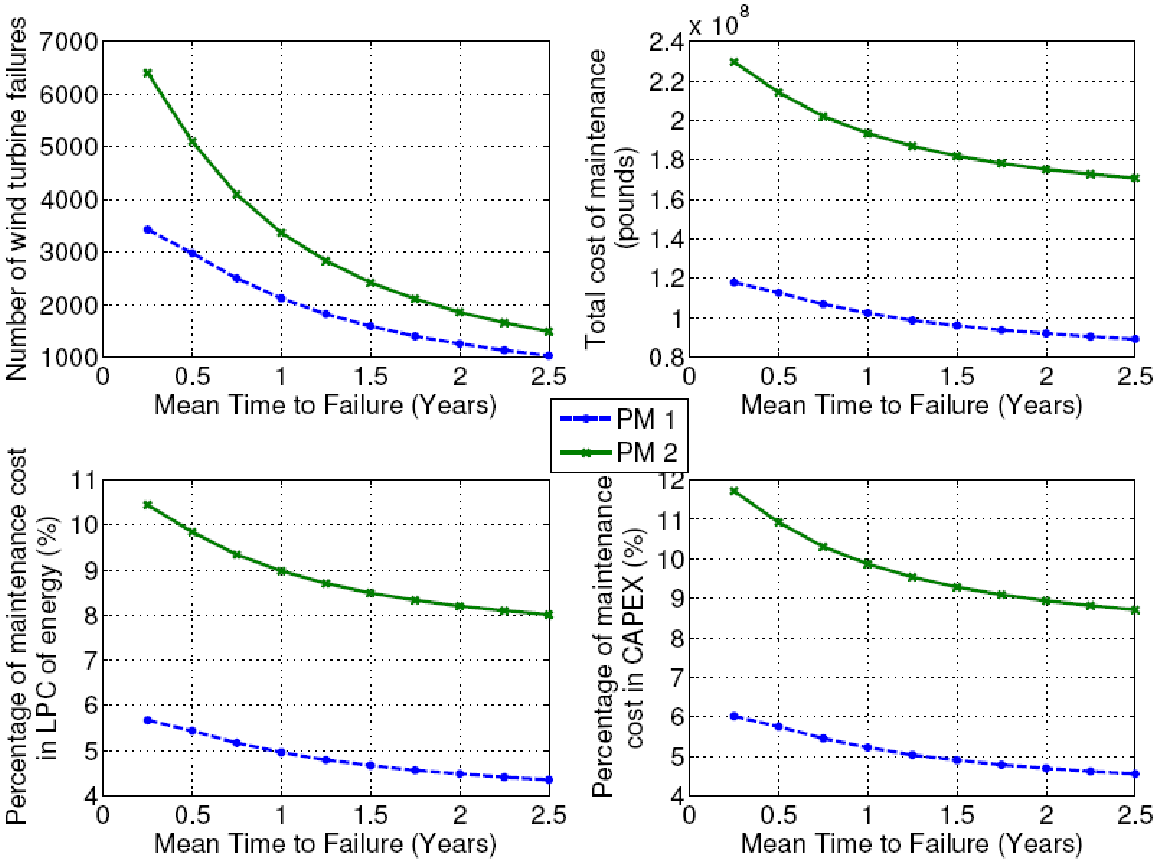

Figure 6.5 The comparison between the planned intervention maintenance strategies, PM1 and PM2, for the London Array offshore wind farm in terms of number of wind turbine failures, total cost of maintenance, percentage of maintenance cost in LPC of energy and percentage of maintenance cost in CAPEX

Considering the number of wind turbine failures versus wind turbine MTTF, the ‘PM 1’ scenario deals with lower number of failures, as compared to the ‘PM 2’ scenario, this being explained by the fact that for ‘PM 2’ scenario the failed wind turbines are being repaired twice a year, however as the wind turbine MTTF increases then the difference between the two curves tends to reduce as a result of higher wind turbine reliability levels. The interesting point to observe in these results is that when employing the ‘PM 1’ scenario the wind turbines that fail between the scheduled maintenance visits remain in a failure mode for longer period, as compared to the ‘PM 2’ scenario, which in turn results in higher energy loss.

Now consider the total cost of maintenance versus wind turbine MTTF in Figure 6.5. The ‘PM 2’ scenario yields higher costs of maintenance as compared to the ‘PM 1’ scenario, this being explained by the higher number of wind turbine failures and consequently higher number of repairs, while also considering the costs incurred for the preventive maintenance of the wind turbines, as previously explained for Figure 6.1 in paragraph 6.2. As the wind turbine MTTF increases the total cost of maintenance for both scenarios decreases, this being a result of lower number of repairs. The significant conclusion reached from these results is that as the wind turbine reliability increases then the cost of maintenance decreases as would be expected from the economical model previously presented in Chapter 4 (p. 105).

Now consider the percentage of maintenance cost in the LPC of energy versus wind turbine MTTF in Figure 6.5. The percentage of maintenance cost in the LPC of energy, represents the OPEX, which is calculated based on equation 4.8, as previously presented for the economic model in Chapter 4 (p. 105). These results can be used for comparing the planned intervention maintenance policy against published data for the corrective maintenance strategy in terms of percentage of maintenance cost in the LPC of energy. For the ‘PM 2’ scenario the cost of maintenance is between 8% and 10.5% of the LPC of energy, whilst for the ‘PM 1’ scenario was calculated to be between 4.5% and 5.8%, this being explained by the higher number of wind turbine failures as shown in the previous paragraphs. As the wind turbine MTTF increases the difference between the

‘PM 1’ and ‘PM 2’ curves decreases, which indicates that the maintenance cost in the LPC of energy for the ‘PM 2’ scenario decrease significantly, as compared to the ‘PM 1’ scenario. The significant point to observe in these results is that the effect of increasing wind turbine reliability on the ‘PM 2’ scenario is higher, as compared to the ‘PM 1’ scenario.

Now consider the percentage of maintenance cost in the CAPEX versus wind turbine MTTF as presented in Figure 6.5. The percentage of maintenance cost in CAPEX was calculated by dividing the OPEX with the CAPEX. These results can be used for comparing the planned intervention maintenance policy against published data for the corrective maintenance strategy in terms of percentage of maintenance cost in CAPEX. For the ‘PM 2’ scenario the cost of maintenance is between 8.8% and 11.8% of the CAPEX, whilst for the ‘PM 1’ scenario was calculated to be between 4.5 and 6%, this being explained by the higher number of wind turbine failures, as explained in the previous paragraphs.

Figure 6.5(a) shows the breakdown of maintenance costs as obtained from the simulation results of the planned intervention maintenance policy on the London Array offshore wind farm. It can be observed that the higher cost incurred is the cost of purchasing replacement items for the failed ones, which includes the costs of exchange items. The repair of the failed items includes the cost of hiring the transportation means, i.e. vessels or helicopters, and the cost of labour. The preventive maintenance costs include the cost of hiring the helicopters, and the labour costs for inspections and preventive maintenance tasks.

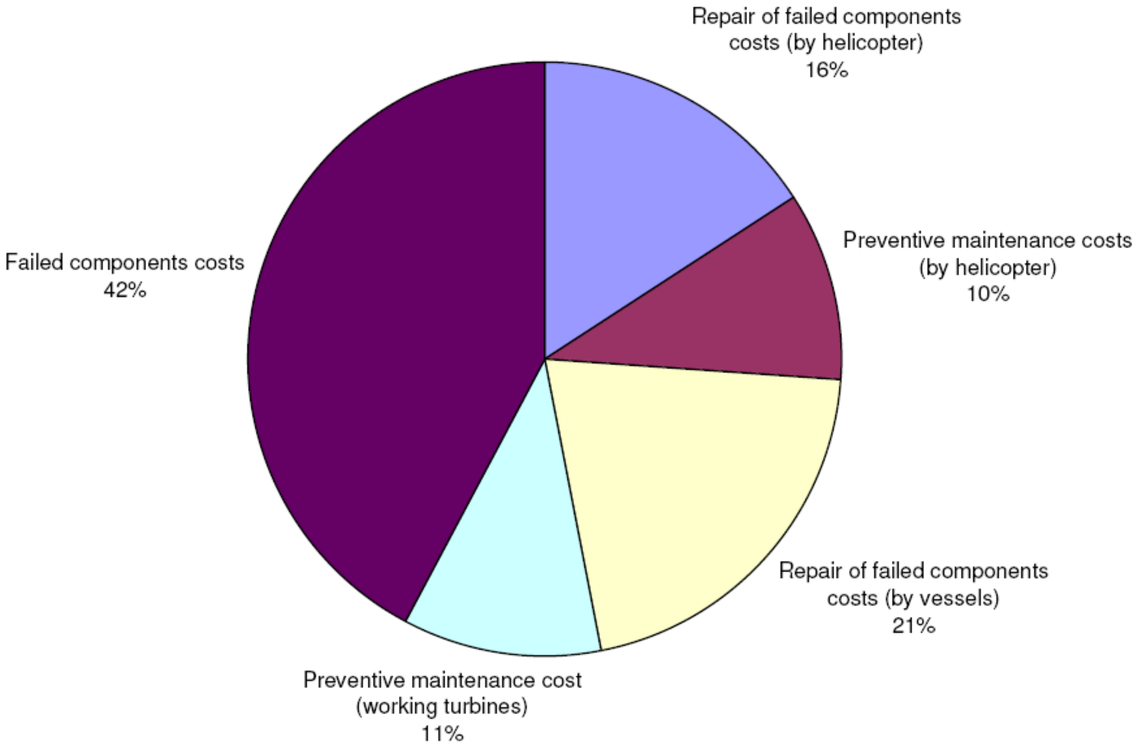

Figure 6.5(a) A pie chart showing the maintenance cost breakdown when using the planned intervention maintenance policy for the London Array offshore wind farm

6.2.5 Discussion on the simulated results from case study 1

The investigations on the planned intervention maintenance policy for the London Array offshore wind farm appear to indicate that the decision on the preferred maintenance scenario, i.e. 'PM 1' or 'PM 2', depends upon a number of input parameters and performance of the project, e.g. the reliability of the wind turbines, the wind turbine repair time, the capacity factor of the wind farm, the maintenance transportation cost, the energy output and the LPC of energy. For wind turbine reliability levels of MTTF>0.35 the 'PM 1' scenario is preferred as it would yield LPC of energy lower, as compared to the 'PM 2' scenario, whilst for wind turbine MTTF higher than 0.35 years then the 'PM 2' scenario would be preferred. This observation indicates that for the London Array offshore wind farm there is a specific wind turbine reliability level, i.e. MTTF=0.35, upon which the decision on the planned intervention maintenance policy scenario could be based.

The variation in the wind turbine mttr and mtpm could result by the change in wind turbine accessibility levels, due to weather and sea state, or availability of transportation means or availability of spare parts. By varying the wind turbine mttr and mtpm for the London Array offshore wind farm the results indicate the significance of energy losses during the scheduled maintenance visits. The simulated results also indicate that by varying the wind turbine mttr and mtpm, then the specific wind turbine reliability level, as explained in the previous paragraph, upon which the decision on the planned intervention maintenance policy scenario could be based on, also varies. A significant conclusion reached from these results is that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the ‘PM 2’ scenario. The same conclusions could be reached when varying the maintenance transportation costs, which could result by the change in the availability of maintenance vessels. The results also indicate that as the transportation costs increase then the specific wind turbine reliability, upon which the decision on the planned intervention maintenance policy scenario could be based on, also increases. The results also indicate that as the hiring cost of maintenance vessels increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the ‘PM 2’ scenario.

The change in the capacity factor of the offshore wind farm could indicate a change in the location or the wind levels of the location. The interesting point to observe from the results of the comparison between the two planned intervention maintenance policy scenarios indicate that as the capacity factor increases the ‘PM 2’ scenario would be preferred over the ‘PM 1’ scenario as it achieves lower LPC of energy.

The number of vessels and helicopters required for the servicing of the wind turbines on each scheduled maintenance visit to the London Array offshore wind farm can be estimated by using the graph for the number of wind turbine failures against wind turbine MTTF as presented in Figure 6.5. For example considering the 'PM 2' scenario as applied to the London Array offshore wind farm with a wind turbine MTTF of 0.5 years, then by using this graph, the number of wind turbine failures is 5,000 on average for 20 years of operation or 125 on average for every scheduled maintenance visit. It has been explained in Chapter 3 (p. 131) and Appendix E that the failures associated with large components that require vessels for servicing account for the 25% of all the failures, which means that 31 failures out of the 125 per scheduled maintenance visit would require the use of a vessel. This would mean that these failures could be serviced by hiring one vessel over one month or two vessels for 15 days by taking into consideration the availability of spare parts and the repair time of 1 day per failure. However, it should be mentioned here that the planned intervention maintenance policy offers significantly increased planning for the maintenance expeditions as the AMP (asset management planning) improves over the operational years of the wind farm, as has been explained in Chapter 3 (p. 80). Similarly the number of helicopters required for servicing the failures of the wind turbines for every scheduled maintenance visit, could be calculated. However, it should be considered that further resources, i.e. helicopters, would be required in addition to the ones considered above, for the completion of the preventive maintenance tasks during the scheduled maintenance visits.

Considering the percentage of maintenance costs in the LPC of energy, the 'PM 2' scenario yields significantly higher results across the range of wind turbine MTTF, as compared to the 'PM 1' scenario, but the LPC of energy for the 'PM 2' scenario is lower as compared to the 'PM 1' scenario for wind turbine MTTF>0.35. This indicates that despite the higher maintenance costs observed for the 'PM 2' scenario, the higher energy output that is achieved, as it benefits from higher wind farm availability, results in lower LPC of energy and shows that the 'PM 2' scenario would be preferred over the 'PM 1' scenario for wind turbine MTTF>0.35. On the other hand, for wind turbine MTTF range of 0.25≤MTTF≤0.35 the 'PM 1' scenario would be preferred, since it achieves higher energy output and lower LPC of energy, as compared to the 'PM 2' scenario, which suffers from higher energy loss due to the planned intervention maintenance policy nature.

6.3 Case Study 2 – Beatrice Offshore Wind Farm

The Beatrice offshore wind farm is a prototype offshore wind farm located near-shore. Table 6.2 gives the input parameters of the Beatrice offshore wind farm, which were used to determine mean wind farm availability, cumulative energy output and LPC of energy.

Table 6.2 Beatrice offshore wind farm parameters.[93,94]

Parameters	**Value**
Turbine Power rating	5 MW
Number of Turbines	2
Distance to shore	25 km
Annual interest rate	5%
Economic lifetime of project	20 years
Capacity factor	35%
Cost of maintenance vessel (cranes)	25,000 pounds (daily rate)
Cost of helicopters or small vessels	5,000 pounds (daily rate)
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Decommissioning	2.5% of capital investment cost
Capital Investment cost	35 million pounds

Figure 6.6 shows a comparison between the 'PM 1' (blue) and PM 2' (green) scenarios of the planned intervention maintenance policy for the Beatrice offshore wind farm, whereby the outputs are presented in terms of wind farm availability, cumulative energy output and LPC of energy, which have been plotted against wind turbine MTTF.

Considering wind farm availability versus the wind turbine MTTF in Figure 6.6, then the two curves representing the 'PM 1' and 'PM 2' scenarios indicate how the wind farm availability increases with increasing wind turbine MTTF, as would be expected. The 'PM 2' scenario yields higher availability levels as compared to the 'PM 1' scenario, this being explained by the fact that 'PM 2' scenario has twice as many scheduled maintenance visits to the offshore wind farm each year. As the wind turbine MTTF increases the difference of wind farm availability between the two curves decreases, which indicates that as the wind turbines become more reliable the difference in wind farm availability between the two scenarios tends to minimise, as would be expected.

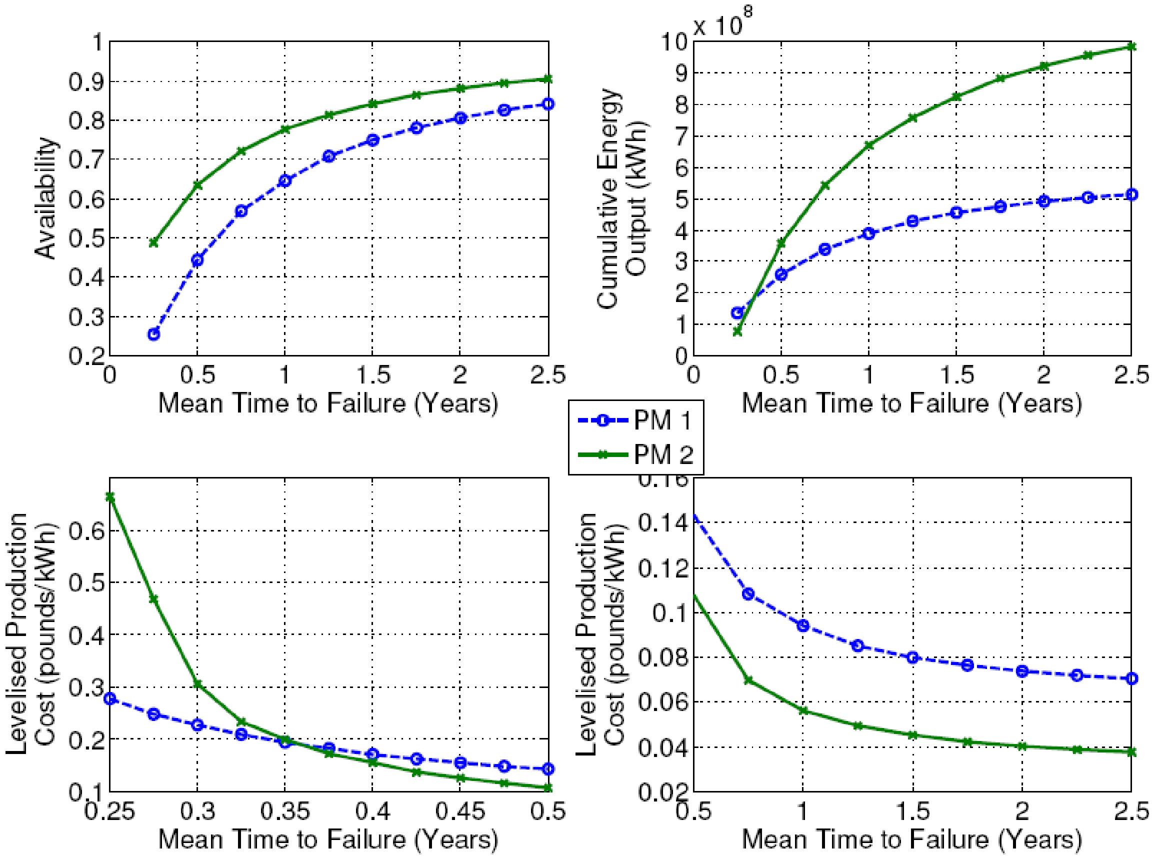

Figure 6.6 The comparison between the planned intervention maintenance policy scenarios, PM1 and PM2, for the Beatrice offshore wind farm, in terms of wind farm availability, cumulative energy output and LPC of energy

Now consider the energy output versus wind turbine MTTF in Figure 6.6. The ‘PM 2’ curve intersects the ‘PM 1’ curve at a wind turbine MTTF of 0.34 years. For wind turbine MTTF levels lower than 0.34 years the ‘PM 1’ scenario yields higher energy output compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF levels higher than 0.34 years the ‘PM 2’ scenario yields higher energy output. These curves can be explained by considering the energy losses during the scheduled maintenance periods, as previously explained for the London Array offshore wind farm. The curves also indicate that as the wind turbine MTTF decreases then more wind turbines will fail during the year so the cumulative repair time for all the wind turbines in the offshore wind farm increases, which in turn results in higher energy losses for the ‘PM 2’ scenario, as compared to the ‘PM 1’ scenario, for MTTF levels of 0.34 years and lower.

Now consider the LPC of energy versus the wind turbine MTTF in Figure 6.6, which is presented in two different graphs for two wind turbine MTTF ranges, i.e. $0.25 \leq MTTF \leq 0.5$ and $0.5 \leq MTTF \leq 2.5$. Considering the LPC of energy for $0.25 \leq MTTF \leq 0.5$, then the ‘PM 1’ curve intersect the ‘PM 2’ curve at a wind turbine MTTF of 0.36 years. For wind turbine MTTF levels lower than 0.36 years the ‘PM 1’ scenario yields lower LPC of energy as compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF levels higher than 0.36 years the ‘PM 2’ scenario yields lower LPC of energy, this being a result of the energy output change discussed in the previous paragraph, since the LPC of energy and the energy output are inversely proportional, as discussed earlier in Chapter 4 (p. 110). Considering the LPC of energy for $0.5 \leq MTTF \leq 2.5$ then the curve for ‘PM 2’ shows significantly lower results as compared to the ‘PM 1’ curve, this being explained by the higher energy output as the wind turbine MTTF increases. This observation indicates that as the wind turbine reliability increases then the ‘PM 2’ scenario would be preferred over the ‘PM 1’ scenario.

When comparing these results with the baseline London Array offshore wind farm, then it can be observed that the two curves for ‘PM 1’ and ‘PM 2’ scenarios for the Beatrice offshore wind farm intersect at higher wind turbine MTTF for both the energy output and LPC of energy, which can be explained by the low number of wind turbines in the Beatrice offshore wind farm and the high cost per installed wind turbine, i.e. CAPEX divided by the number of wind turbines (17.5 million pounds), as compared to the London Array offshore wind farm (11.2 million pounds per installed wind turbine). The significant conclusions reached from the above observations is that a more reliable wind turbine is required for the Beatrice offshore wind farm to produce results in terms of LPC that are competitively comparable with the London Array offshore wind farm.

6.3.1 The effect of mean time to repair

Figure 6.7 shows the effect of varying the wind turbine mttr and mtpm on the cumulative energy output (upper graphs) and LPC of energy (lower graphs), plotted against wind turbine MTTF, for comparing the planned intervention maintenance scenarios, 'PM 1' (blue) and 'PM 2' (green). This figure was constructed to investigate how the intersection point between the two curves, i.e. 'PM 1' and 'PM 2', changes by varying the wind turbine mttr and mtpm, as being a significant conclusion of the results in Figure 6.6. The four graphs in Figure 6.7 are divided into two sections; the left section consisting of two graphs for the 'low mttr' simulations, and the right sections also consisting of two graphs for the 'high mttr' simulations. Two different values for the wind turbine mttr and mtpm have been investigated; 'low mttr', which simulates half the input parameter values of mttr and mtpm, i.e. mttr=0.75 days and mtpm=0.5 days (left section graphs), and 'high mttr', which simulates two fold the input parameter values of mttr and mtpm i.e. mttr=3 days and mtpm=2 days (right section graphs).

Considering the energy output versus the wind turbine MTTF (upper graphs) in Figure 6.7, it can be observed that for the 'low mttr' graph, the intersection point between the 'PM 1' and 'PM 2' curves reduces to wind turbine MTTF of 0.33 years, as compared to the results shown in Figure 6.6, whilst for the 'high mttr' graph the intersection point between the 'PM 1' and 'PM 2' curves increases to wind turbine MTTF of 0.345 years, as compared to the results shown in Figure 6.6. These results indicate that as the repair time of the wind turbines increases then the 'PM 1' scenario yields higher energy output for a larger wind turbine MTTF range, as compared to the 'PM 2' scenario.

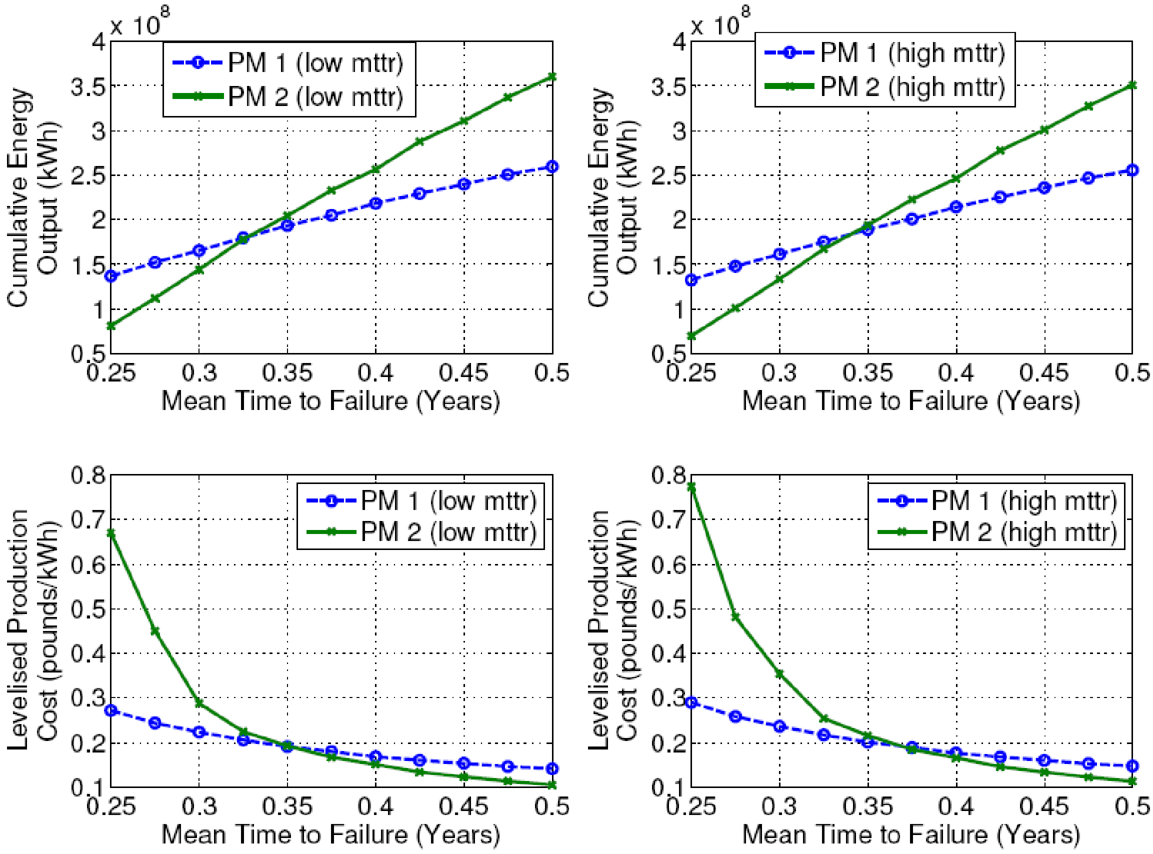

Figure 6.7 The effect of mttr and mtpm on the cumulative energy output and LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the Beatrice offshore wind farm

Now consider the LPC of energy versus the wind turbine MTTF (lower graphs) in Figure 6.7, it can be observed that for the 'low mttr' graph, the intersection point between the 'PM 1' and 'PM 2' curves reduces to wind turbine MTTF of 0.35 years, whilst for the 'high mttr' graph, the intersection point between the 'PM 1' and 'PM 2' curves increases to wind turbine MTTF of 0.37 years, as compared to the results shown in Figure 6.6. These results indicate that as the repair time of the wind turbines increases then the 'PM 1' scenario yields lower LPC of energy for a larger wind turbine MTTF range, as compared to the 'PM 2' scenario, and would therefore be preferred over the 'PM 2' scenario.

6.3.2 The effect of the capacity factor

Figure 6.8 shows the effect of varying the capacity factor of the Beatrice offshore wind farm, which could result from the change in wind farm location or a change in the windiness of the wind farm. Two different capacity factors have been used, i.e. 25% and 45%, to produce results in terms of cumulative energy output and LPC of energy, all plotted against wind turbine MTTF. The six graphs in Figure 6.8 are used to compare the 'PM 1' (blue) and 'PM 2' (green) scenarios of the planned intervention maintenance policy. The graphs in Figure 6.8 have been divided into two sections with a dividing line between them. The left section, consisting of three graphs, presents the results for a capacity factor of 25% and the right section presents the results for a capacity factor of 45%. The axes limits on the related graphs have been set identical, to assist the comparison between the two sections.

Considering the energy output versus the wind turbine MTTF (two upper graphs), it can be observed that the 'PM 2' scenario achieves higher energy output for both the capacity factors that have been simulated, as compared to 'PM 1' scenario, this being explained by the fact that 'PM 2' scenario has twice as many scheduled maintenance visits to the offshore wind farm each year. What is interesting to observe in these graphs is that as the capacity factor increases the difference in energy output between the two curves also increases, which indicates that for wind turbine MTTF>0.35, as the capacity factor increases the 'PM 2' scenario would be preferred, over the 'PM 1' scenario.

Now consider the LPC of energy versus the wind turbine MTTF (four lower graphs). Two different wind turbine MTTF ranges have been used to present the comparison between the 'PM 1' and 'PM 2' scenarios, i.e. 0.25≤MTTF≤0.5 and 0.5≤MTTF≤2.5. Considering the LPC of energy for 0.25≤MTTF≤0.5 (two middle graphs), the 'PM 1' curve intersect the 'PM 2' curve at a value of LPC of energy 0.18 £/kWh for a capacity factor of 45%, which is found to be lower as compared to a capacity factor of 25% (0.28 £/kWh), which indicates that for 0.25≤MTTF≤0.5, as the capacity factor increases the difference in LPC of energy between the 'PM 1' and 'PM 2' curves decreases.

Considering the LPC of energy for 0.5≤MTTF≤2.5 (two lower graphs), the comparison between the two scenarios indicates that the difference in LPC of energy between the two curves also decreases when the capacity factor of the wind farm increases. The significant point when observing the results simulated for Figure 6.8 is that as the capacity factor increases the preference of 'PM 2' scenario over the 'PM 1' scenario tends to increase, as it achieves higher energy output and lower LPC of energy.

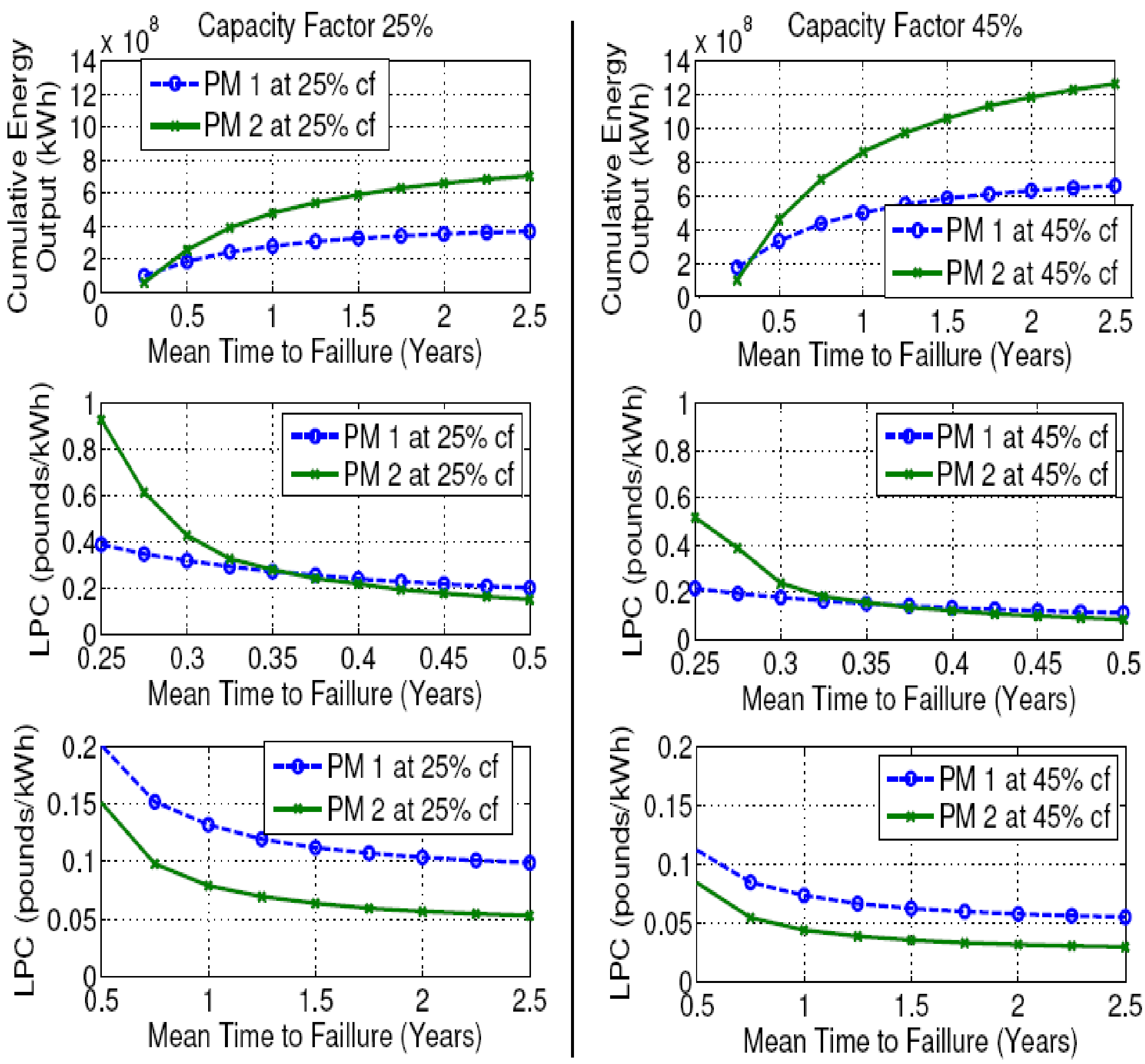

Figure 6.8 The effect of the capacity factor on the cumulative energy output and LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the Beatrice offshore wind farm

6.3.3 The effect of the transportation costs

Figure 6.9 shows the effect of varying the cost of transportation means on the LPC of energy, plotted against wind turbine MTTF, for comparing the planned intervention maintenance scenarios, 'PM 1' (blue) curve and 'PM 2' (green) curve for the Beatrice offshore wind farm. This figure was constructed to investigate how the intersection point between the two curves changes by varying the cost of transportation means. The variation in the hiring cost of maintenance vessels is associated with the availability of the vessels, as previously explained for the London Array offshore wind farm. Two different input parameter values for the cost of maintenance vessels have been investigated; 10,000 and 100,000 pounds as a daily rate for hiring the vessels.

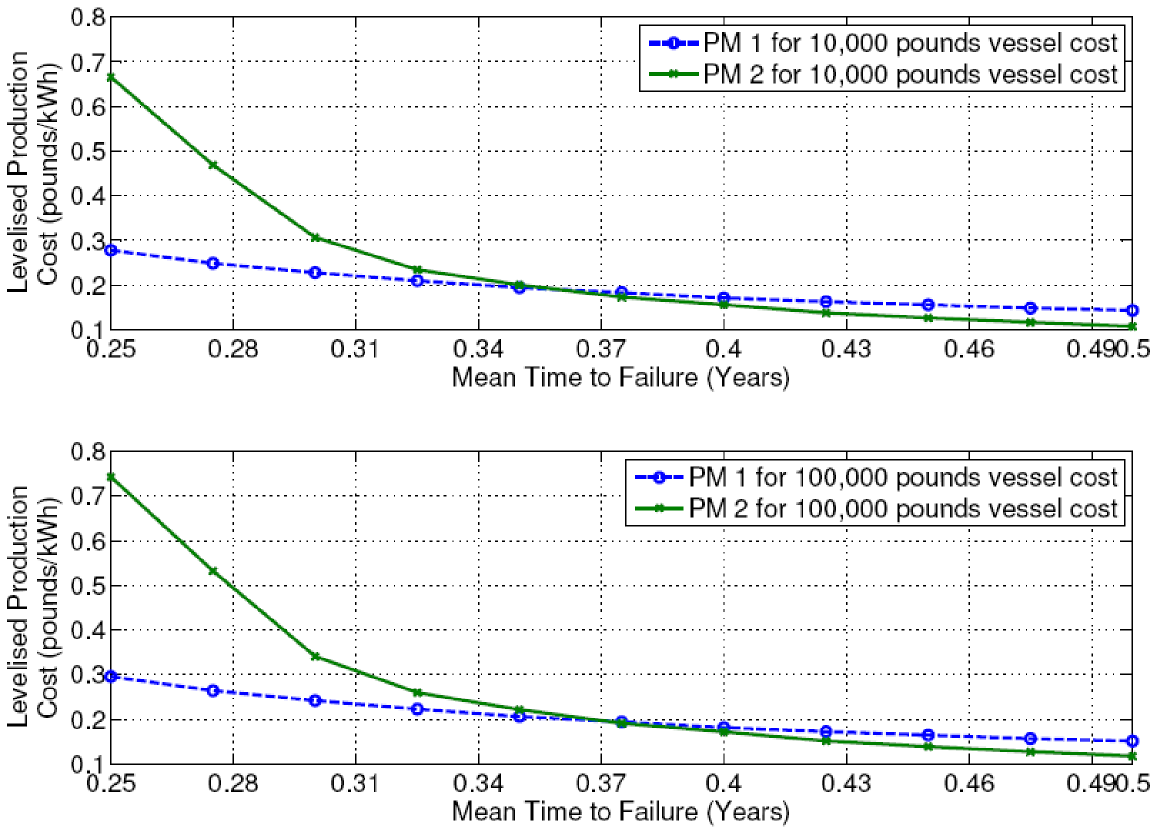

Figure 6.9 The effect of the cost of transportation means on the LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the Beatrice offshore wind farm

Considering the LPC of energy versus the wind turbine MTTF for vessel hiring costs of 10,000 pounds then it can be observed that the intersection point between the ‘PM 1’ and ‘PM 2’ curves reduces to wind turbine MTTF of 0.345 years, as compared to the results presented in Figure 6.6, whilst by increasing the cost of vessel hiring to 100,000 pounds, then the intersection point of the of the ‘PM 1’ and ‘PM 2’ curves increases to wind turbine MTTF of 0.37 years, as compared to the results in Figure 6.6. An interesting point that these results indicate is that as the cost of maintenance vessels increases then the ‘PM 1’ scenario yields lower LPC of energy and consequently would be preferred over the ‘PM 2’ scenario, for larger wind turbine MTTF range.

6.3.4 The effect of the number of failures

Figure 6.10 shows the comparison between the ‘PM 1’ (blue) and PM 2’ (green) scenarios of planned intervention maintenance policy for the Beatrice offshore wind farm, where the outputs are presented in terms of the number of wind turbine failures, total cost of maintenance, percentage of maintenance cost in LPC of energy, and percentage of maintenance costs in CAPEX, which have been plotted against wind turbine MTTF.

Now considering the number of wind turbine failures versus wind turbine MTTF. The ‘PM 1’ scenario deals with lower number of failures, as compared to the ‘PM 2’ scenario, this being explained by the fact that for ‘PM 2’ scenario the failed wind turbines are being repaired twice a year. However, as the wind turbine MTTF increases then the difference between the two curves tends to minimise as a result of higher wind turbine reliability levels. The interesting point to observe in these results is that when employing the ‘PM 1’ scenario the wind turbines that fail between the scheduled maintenance visits remain in a failed mode for longer period, as compared to the ‘PM 2’ scenario, which in turn results in higher energy loss.

Now consider the total cost of maintenance versus wind turbine MTTF in Figure 6.10. The ‘PM 2’ scenario yields higher costs of maintenance as compared to the ‘PM 1’ scenario, this being explained by the higher number of wind turbine failures and consequently higher number of repairs, while also considering the costs incurred for the preventive maintenance of the wind turbines, as previously explained for Figure 6.1 in paragraph 6.2. As the wind turbine MTTF increases the total cost of maintenance for both scenarios decreases, this being a result of lower number of repairs. The significant conclusion reached from these results is that as the wind turbine reliability increases, then the cost of maintenance decreases as would be expected from the economic model previously presented in Chapter 4 (p. 105).

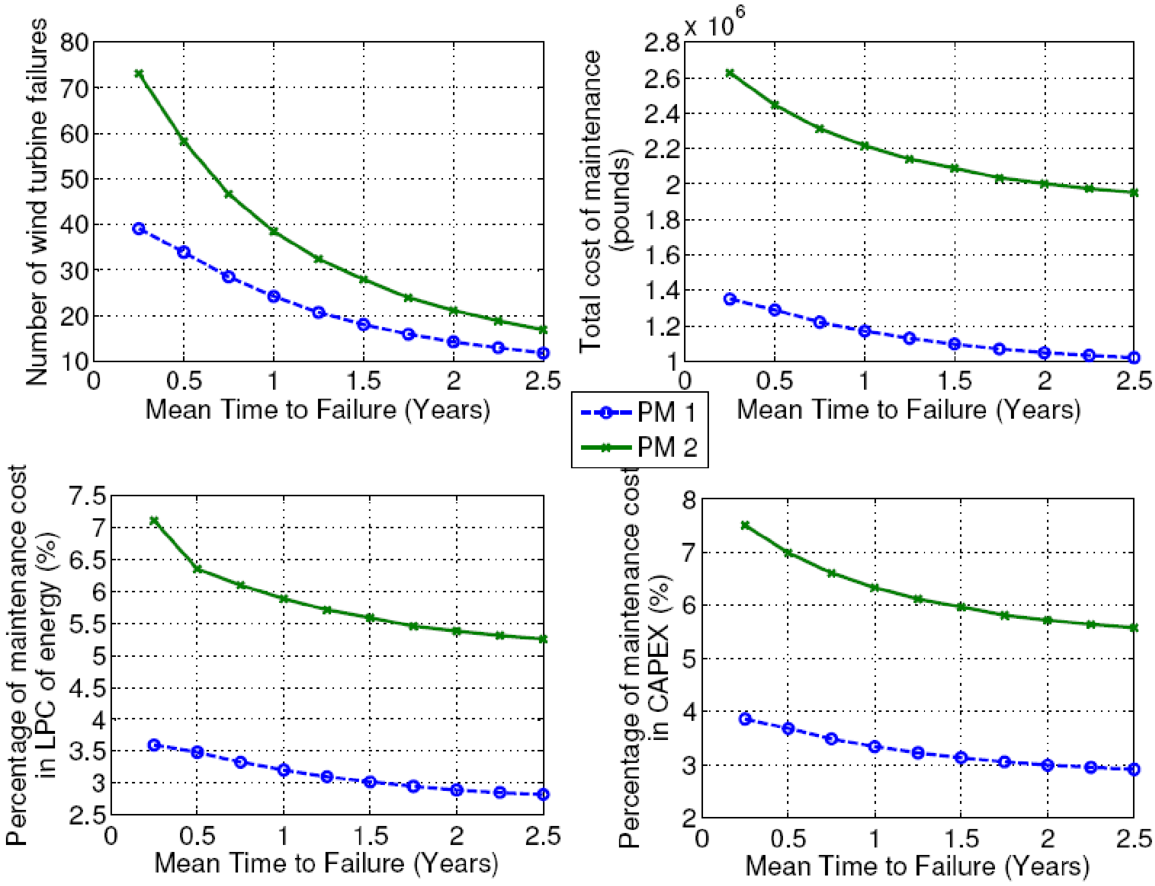

Figure 6.10 The comparison between the planned intervention maintenance strategies, PM1 and PM2, for the Beatrice offshore wind farm in terms of number of wind turbine failures, total cost of maintenance, percentage of maintenance cost in LPC of energy and percentage of maintenance cost in CAPEX

Now consider the percentage of maintenance cost in the LPC of energy versus wind turbine MTTF in Figure 6.10. The percentage of maintenance cost in the LPC of energy represents the OPEX, which is calculated based on equation 4.8, as previously presented for the economic model in Chapter 4 (p. 105). These results can be used for comparing the planned intervention maintenance policy against published data for the corrective maintenance strategy in terms of percentage of maintenance cost in the LPC of energy. For the ‘PM 2’ scenario the cost of maintenance is between 5.25% and 7.1% of the LPC of energy, whilst for the ‘PM 1’ scenario was calculated to be between 2.8% and 3.6%, this being explained by the higher number of wind turbine failures as shown in the previous paragraphs. As the wind turbine MTTF increases the difference between the ‘PM 1’ and ‘PM 2’ curves decreases, which indicates that the maintenance cost in the LPC of energy for the ‘PM 2’ scenario decrease significantly, as compared to the ‘PM 1’ scenario. The significant point to observe in these results is that the effect of increasing wind turbine reliability on the ‘PM 2’ scenario is higher, as compared to the ‘PM 1’ scenario.

Now consider the percentage of maintenance cost in the CAPEX versus wind turbine MTTF as presented in Figure 6.10. The percentage of maintenance cost in CAPEX was calculated by dividing the OPEX with the CAPEX. These results can be used for comparing the planned intervention maintenance policy against published data on the corrective maintenance strategy in terms of percentage of maintenance cost in CAPEX. For the ‘PM 2’ scenario the cost of maintenance is between 5.6% and 7.5% of the CAPEX, whilst for the ‘PM 1’ scenario was calculated to be between 3 and 4%, this being explained by the higher number of wind turbine failures, as explained in the previous paragraphs. As the wind turbine MTTF increases the difference between the ‘PM 1’ and ‘PM 2’ curves decreases, which indicates that the rate of change of the percentage of maintenance cost in the CAPEX for the ‘PM 2’ scenario is increasing, as compared to the ‘PM 1’ scenario.

6.3.5 Discussion on the simulated results from case study 2

The investigations on the planned intervention maintenance policy for the Beatrice offshore wind farm indicate that the decision on the preferred maintenance scenario, i.e. ‘PM 1’ or ‘PM 2’, depends on a number of input parameters and outputs of the project, e.g. the reliability of the wind turbines, the wind turbine repair time, the capacity factor of the wind farm, the maintenance transportation cost, the energy output and the LPC of energy. For wind turbine reliability levels of MTTF>0.36 the ‘PM 1’ scenario is preferred as it would yield LPC of energy lower, as compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF higher than 0.36 years then the ‘PM 2’ scenario would be preferred. This observation indicates that for the Beatrice offshore wind farm there is a specific wind turbine reliability level, i.e. MTTF=0.36, upon which the decision on the planned intervention maintenance policy scenario could be based. When comparing the results from the Beatrice offshore wind farm to the results presented earlier for the London Array offshore wind farm, then it can be observed that the wind turbine MTTF range, for which the ‘PM 1’ scenario is preferred over the ‘PM 2’ scenario is larger for the Beatrice offshore wind farm, which indicates that for prototype projects with low number of wind turbines, the ‘PM 1’ scenario would yield lower LPC of energy for a larger range of wind turbine reliability.

The variation in the wind turbine mttr and mtpm could result by the change in wind turbine accessibility levels, due to weather and sea state, or availability of transportation means or availability of spare parts. By varying the wind turbine mttr and mtpm for the Beatrice offshore wind farm the results indicate the significance of energy losses during the scheduled maintenance visits. The simulated results also indicate that by varying the wind turbine mttr and mtpm, then the specific wind turbine reliability level, as explained in the previous paragraph, upon which the decision on the planned intervention maintenance policy scenario could be based on, also varies. A significant conclusion reached from these results is that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range. The same conclusions could also be reached when varying the maintenance transportation costs, which could result by the change in the availability of maintenance vessels. The results indicate that as the transportation costs increase then the specific wind turbine reliability, upon which the decision on the planned intervention maintenance policy scenario could be based on, also increases. The results also indicate that as the hiring cost of maintenance vessels increases then the 'PM 1' scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the 'PM 2' scenario.

The change in the capacity factor of the offshore wind farm could indicate a change in the location (i.e. different case studies) or the wind levels of the location. The interesting point to observe from the results of the comparison between the two planned intervention maintenance policy scenarios indicate that as the capacity factor increases the 'PM 2' scenario would be preferred over the 'PM 1' scenario as it achieves lower LPC of energy.

Considering the percentage of maintenance costs in the LPC of energy, the 'PM 2' scenario yields significantly higher results across the range of wind turbine MTTF, as compared to the 'PM 1' scenario, but the LPC of energy for the 'PM 2' scenario is lower as compared to the 'PM 1' scenario for wind turbine MTTF>0.36. This indicates that despite the higher maintenance costs observed for the 'PM 2' scenario, the higher energy output that is achieved, as it benefits from higher wind farm availability, results in lower LPC of energy and shows that the 'PM 2' scenario would be preferred over the 'PM 1' scenario for wind turbine MTTF>0.36. On the other hand, for wind turbine MTTF range of 0.25≤MTTF≤0.36 the 'PM 1' scenario would be preferred since it achieves higher energy output and lower LPC of energy, as compared to the 'PM 2' scenario, which suffers from higher energy loss due to the planned intervention maintenance policy nature.

6.4 Case Study 3 – Kentish Flats Offshore Wind Farm

The Kentish Flats offshore wind farm is located in the UK at the Thames Estuary which is online since 2005 feeding the national grid. Table 6.3 gives the input parameters of the Kentish Flats offshore wind farm, which were used to determine mean wind farm availability, cumulative energy output and LPC of energy.

Table 6.3 Kentish Flats offshore wind farm parameters.[94,95]

Parameters	Value
Turbine Power rating	3 MW
Number of Turbines	30
Distance to shore	10 km
Annual interest rate	5%
Economic lifetime of project	20 years
Capacity factor	35%
Cost of maintenance vessel (cranes)	25,000 pounds (daily rate)
Cost of helicopters or small vessels	5,000 pounds (daily rate)
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Decommissioning	2.5% of capital investment cost
Capital Investment cost	105 million pounds

Figure 6.11 shows a comparison between the 'PM 1' (blue) and PM 2' (green) scenarios of the planned intervention maintenance policy for the Kentish Flats offshore wind farm, whereby the outputs are presented in terms of wind farm availability, cumulative energy output and LPC of energy, which have been plotted against wind turbine MTTF.

Considering wind farm availability versus the wind turbine MTTF in Figure 6.11 then the two curves representing the 'PM 1' and 'PM 2' scenarios indicate how the wind farm availability increases with increasing wind turbine MTTF, as would be expected. The ‘PM 2’ scenario yields higher availability levels, as compared to the ‘PM 1’ scenario, this being explained by the fact that ‘PM 2’ scenario has twice as many scheduled maintenance visits to the offshore wind farm each year. As the wind turbine MTTF increases the difference of wind farm availability between the two curves decreases, which indicates that as the wind turbines become more reliable the difference in wind farm availability between the two scenarios tends to minimise, as would be expected.

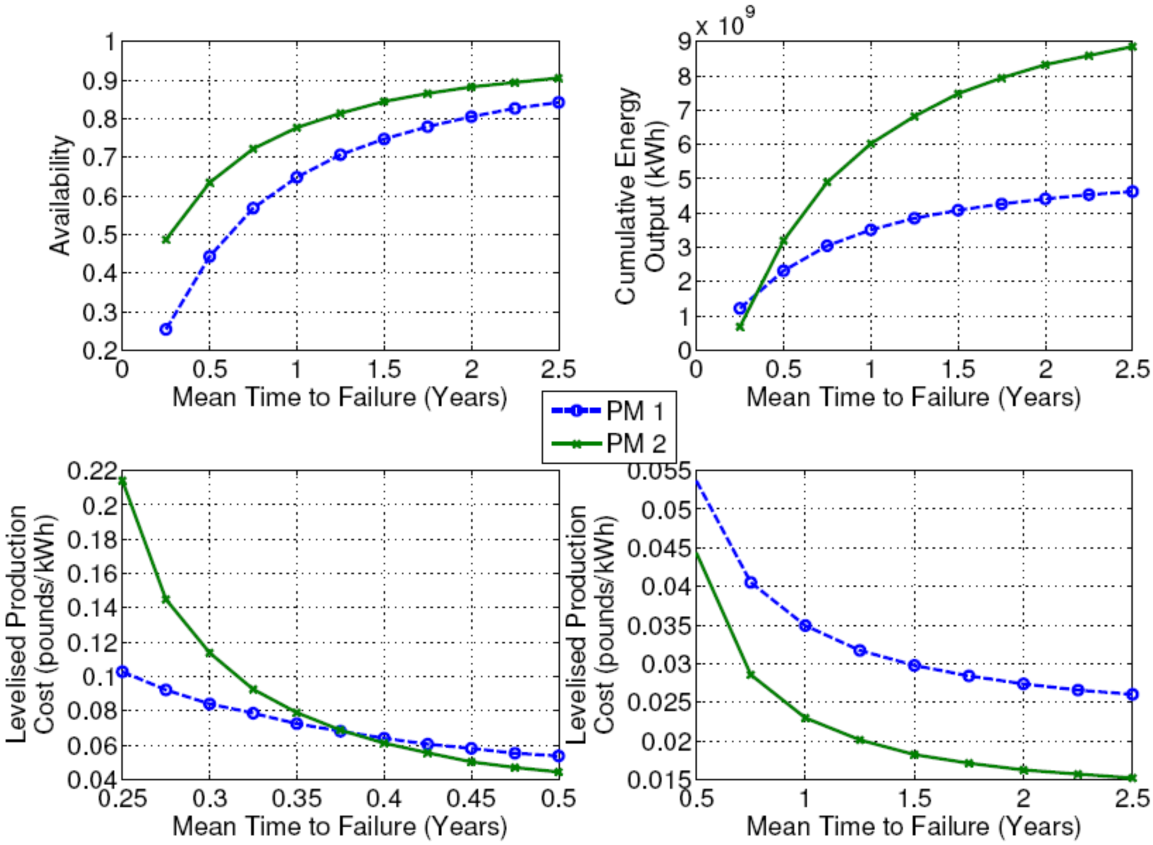

Figure 6.11 The comparison between the planned intervention maintenance policy scenarios, PM1 and PM2, for the Kentish Flats offshore wind farm, in terms of wind farm availability, cumulative energy output and LPC of energy

Now consider the energy output versus wind turbine MTTF in Figure 6.11. The ‘PM 2’ curve intersects the ‘PM 1’ curve at a wind turbine MTTF of 0.34 years. For wind turbine MTTF levels lower than 0.34 years the ‘PM 1’ scenario yields higher energy output, as compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF levels higher than 0.34 years the ‘PM 2’ scenario yields higher energy output. These curves can be explained by considering the energy losses during the scheduled maintenance periods, as previously explained for the London Array offshore wind farm. The curves also indicate that as the wind turbine MTTF decreases then more wind turbines will fail during the year so the cumulative repair time for all the wind turbines in the offshore wind farm increases, which in turn results in higher energy losses for the ‘PM 2’ scenario, as compared to the ‘PM 1’ scenario, for MTTF levels of 0.34 years and lower.

Now consider the LPC of energy versus the wind turbine MTTF in Figure 6.11, which is presented in two different graphs for two wind turbine MTTF ranges, i.e. $0.25 \leq MTTF \leq 0.5$ and $0.5 \leq MTTF \leq 2.5$. Considering the LPC of energy for $0.25 \leq MTTF \leq 0.5$, then the ‘PM 1’ curve intersect the ‘PM 2’ curve at a wind turbine MTTF of 0.39 years. For wind turbine MTTF levels lower than 0.39 years the ‘PM 1’ scenario yields lower LPC of energy, as compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF levels higher than 0.39 years the ‘PM 2’ scenario yields lower LPC of energy, this being a result of the energy output change discussed in the previous paragraph, since the LPC of energy and the energy output are inversed proportional, as discussed earlier in Chapter 4 (p. 110). Considering the LPC of energy for $0.5 \leq MTTF \leq 2.5$ then the curve for ‘PM 2’ shows significantly lower results as compared to the ‘PM 1’ scenario, this being explained by the higher energy output as the wind turbine MTTF increases. As the wind turbines become more reliable, i.e. MTTF increases, then the difference between the ‘PM 1’ curve and ‘PM 2’ curve is increasing, indicating that the ‘PM 2’ scenario would be preferred over the ‘PM 1’ curve, for higher levels of wind turbine reliability. This observation indicates that as the wind turbine reliability increases then the ‘PM 2’ scenario would be preferred over the ‘PM 1’ scenario.

6.4.1 The effect of the mean time to repair

Figure 6.12 shows the effect of varying the wind turbine mttr and mtpm on the cumulative energy output (upper graphs) and LPC of energy (lower graphs), plotted against wind turbine MTTF, for comparing the planned intervention maintenance scenarios, ‘PM 1’ (blue) and ‘PM 2’ (green). This figure was constructed to investigate how the intersection point between the two curves, i.e. ‘PM 1’ and ‘PM 2’, changes by varying the wind turbine mttr and mtpm, as being a significant conclusion of the results in Figure 6.11. The four graphs in Figure 6.12 are divided into two sections; the left section consisting of two graphs for the ‘low mttr’ simulations, and the right sections also consisting of two graphs for the ‘high mttr’ simulations. Two different values for the wind turbine mttr and mtpm have been investigated; ‘low mttr’, which simulates half the input parameter values of mttr and mtpm, i.e. mttr=0.75 days and mtpm=0.5 days (left section graphs), and ‘high mttr’, which simulates two fold the input parameter values of mttr and mtpm, i.e. mttr=3 days and mtpm=2 days (right section graphs).

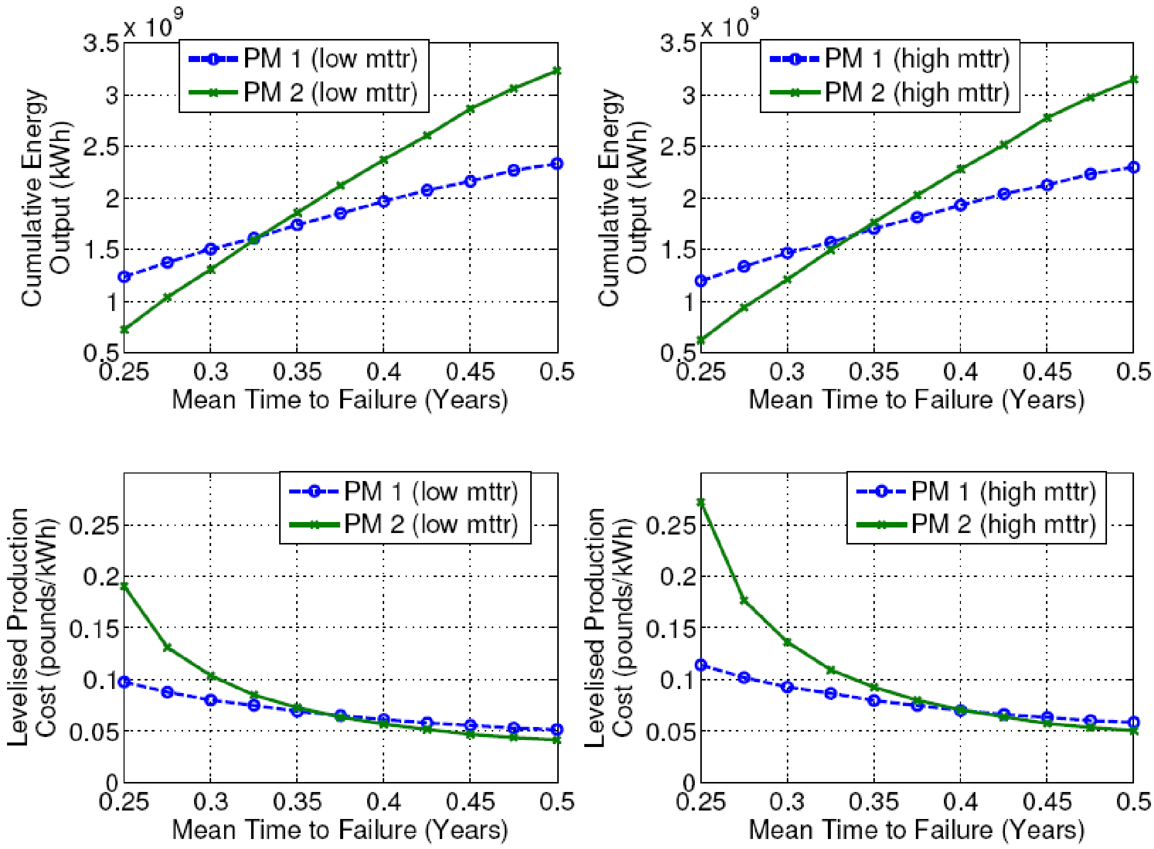

Figure 6.12 The effect of mttr and mtpm on the cumulative energy output and LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the Kentish Flats offshore wind farm

Considering the energy output versus the wind turbine MTTF (upper graphs) in Figure 6.12, it can be observed that for the ‘low mttr’ graph, the intersection point between the ‘PM 1’ and ‘PM 2’ curves reduces to wind turbine MTTF of 0.33 years, as compared to the results shown in Figure 6.11, whilst for the ‘high mttr’ graph, the intersection point between the of the ‘PM 1’ and ‘PM 2’ curves increases to wind turbine MTTF of 0.345 years, as compared to the results shown in Figure 6.11. These results indicate that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields higher energy output for a larger wind turbine MTTF range, as compared to the ‘PM 2’ scenario.

Now consider the LPC of energy versus the wind turbine MTTF (lower graphs) in Figure 6.12, it can be observed that for the ‘low mttr’ graph, the intersection point between the ‘PM 1’ and ‘PM 2’ curves reduces to wind turbine MTTF of 0.38 years, whilst for the ‘high mttr’ graph, the intersection point between the ‘PM 1’ and ‘PM 2’ curves increases to wind turbine MTTF of 0.40 years, as compared to the results shown in Figure 6.11. These results indicate that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, as compared to the ‘PM 2’ scenario, and would therefore be preferred over the ‘PM 2’ scenario.

6.4.2 The effect of the capacity factor

Figure 6.13 shows the effect of varying the capacity factor of the Kentish Flats offshore wind farm, which could result from the change in wind farm location or a change in the windiness of the wind farm. Two different capacity factors have been used, i.e. 25% and 45%, to produce results in terms of cumulative energy output and LPC of energy, all plotted against wind turbine MTTF. The six graphs in Figure 6.13 are used to compare the ‘PM 1’ (blue) and ‘PM 2’ (green) scenarios of the planned intervention maintenance policy. The graphs in Figure 6.13 have been divided into two sections with a dividing line between them. The left section, consisting of three graphs, presents the results for a capacity factor of 25% and the right section presents the results of a capacity factor of 45%. The axes on the related graphs have been set to have the same limits, to assist the comparison between the two sections.

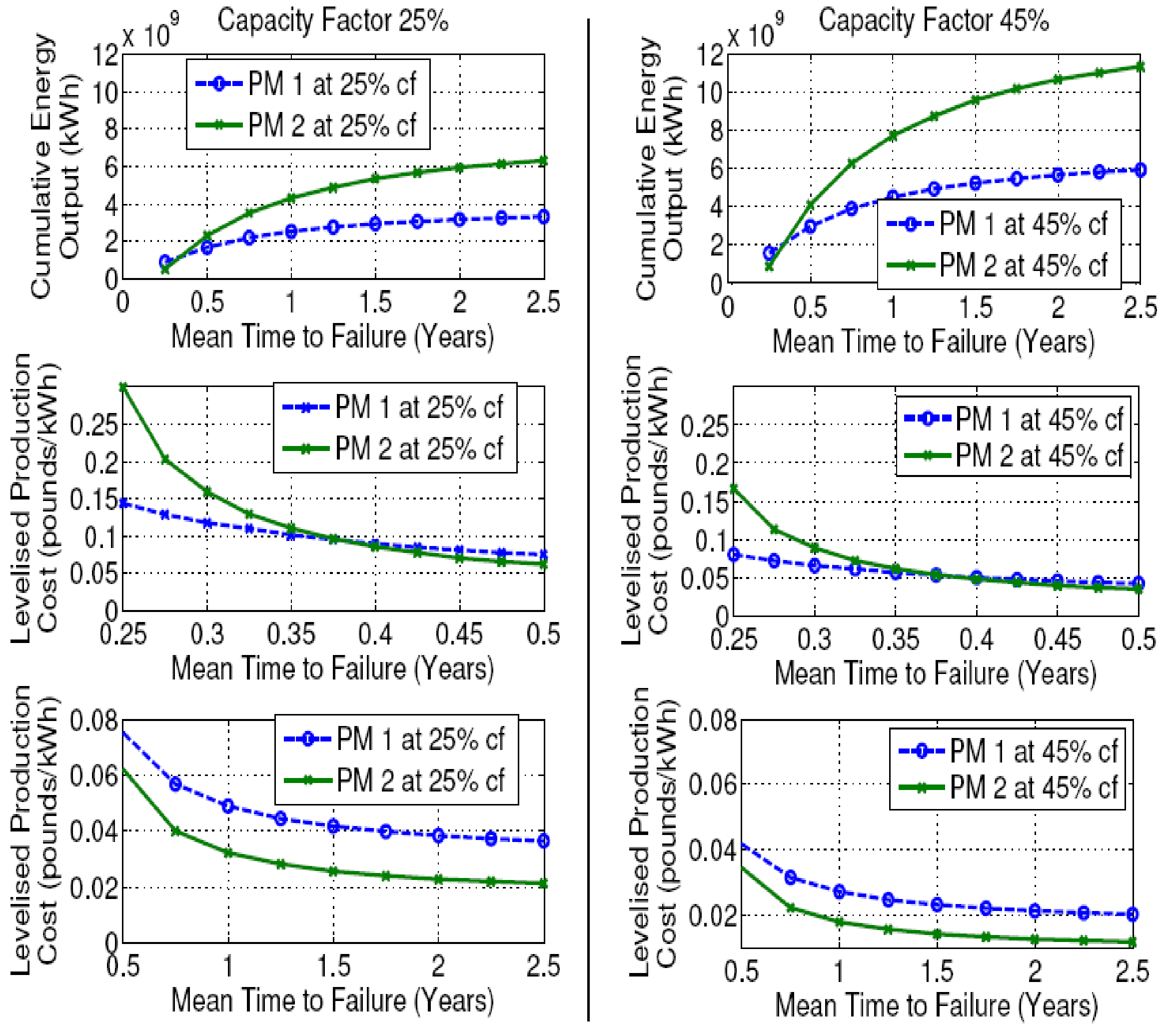

Figure 6.13 The effect of the capacity factor on the cumulative energy output and LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the Kentish Flats offshore wind farm

Considering the energy output versus the wind turbine MTTF (two upper graphs), it can be observed that the ‘PM 2’ scenario achieves higher energy output for both the capacity factors that have been simulated, as compared to ‘PM 1’ scenario, this being explained by the fact that ‘PM 2’ scenario has twice as many scheduled maintenance visits to the offshore wind farm each year. What is interesting to observe in these graphs is that as the capacity factor increases the difference in the energy output between the two curves also increases, which indicates that for wind turbine MTTF>0.34, as the capacity factor increases the 'PM 2' scenario would be preferred over the 'PM 1' scenario.

Now consider the LPC of energy versus the wind turbine MTTF (four lower graphs). Two different wind turbine MTTF ranges have been used to present the comparison between the 'PM 1' and 'PM 2' scenarios, i.e. 0.25≤MTTF≤0.5 and 0.5≤MTTF≤2.5. Considering the LPC of energy for 0.25≤MTTF≤0.5 (two middle graphs), the 'PM 1' curve intersect the 'PM 2' curve at a value of LPC of energy 0.05 £/kWh for a capacity factor of 45%, which is found to be lower as compared to a capacity factor of 25% (0.1 £/kWh), which indicates that for 0.25≤MTTF≤0.5, as the capacity factor increases the difference in LPC of energy between the 'PM 1' and 'PM 2' curves decreases. Considering the LPC of energy for 0.5≤MTTF≤2.5 (two lower graphs), the comparison between the two scenarios indicates that the difference in LPC of energy between the two curves also decreases when the capacity factor of the wind farm increases. The significant point when observing the results simulated for Figure 6.13 is that as the capacity factor increases the preference of 'PM 2' scenario over the 'PM 1' scenario tends to increase, as it achieves higher energy output and lower LPC of energy.

6.4.3 The effect of the transportation costs

Figure 6.14 shows the effect of varying the cost of transportation means on the LPC of energy, plotted against wind turbine MTTF, for comparing the planned intervention maintenance scenarios, 'PM 1' (blue) curve and 'PM 2' (green) curve, for the Kentish Flats offshore wind farm. This figure was constructed to investigate how the intersection point between the two curves changes by varying the cost of transportation means. The variation in the hiring cost of maintenance vessels is associated with the availability of the vessels as previously explained in the paragraphs 6.2 and 6.3. Two different input parameter values for the cost of maintenance vessels have been investigated; 10,000 and 100,000 pounds as a daily rate for hiring the vessels.

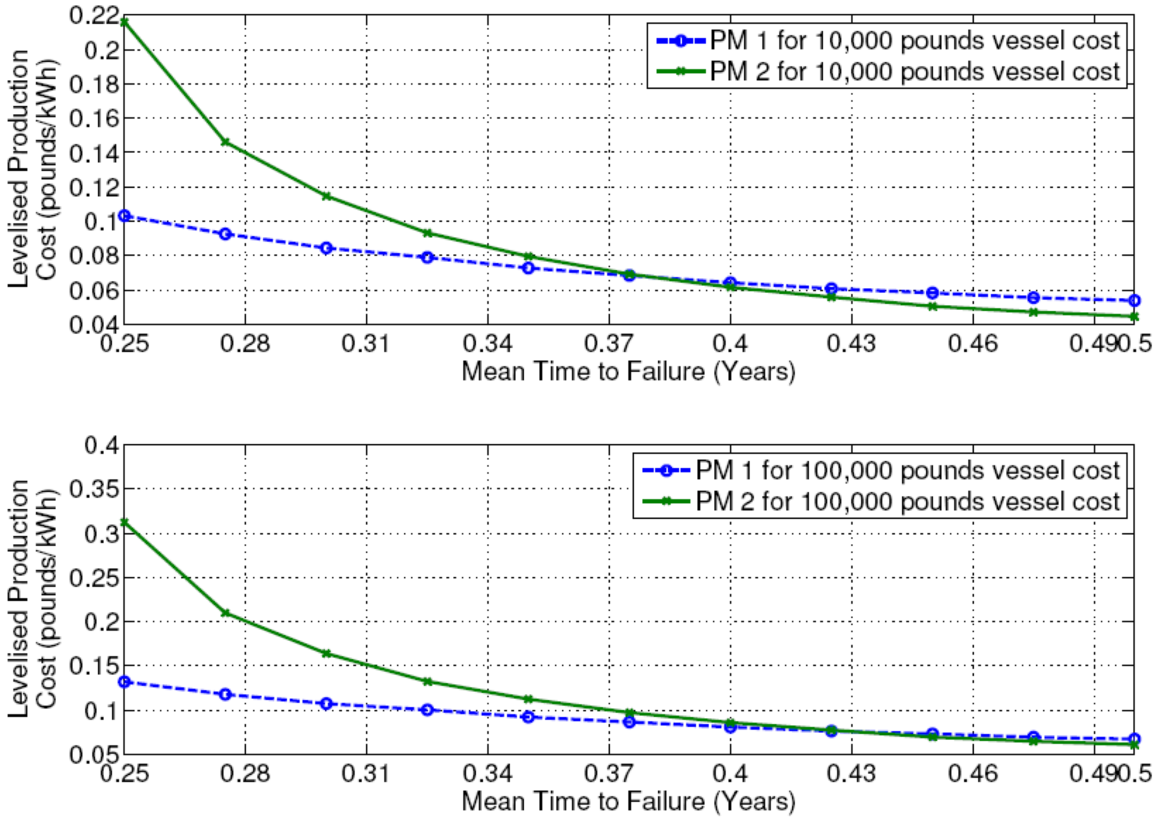

Figure 6.14 The effect of the cost of transportation means on the LPC of energy for the planned intervention maintenance policy scenarios, PM1 and PM2, for the Kentish Flats offshore wind farm

Considering the LPC of energy versus the wind turbine MTTF for vessel hiring costs of 10,000 pounds then it can be observed that the intersection point between the ‘PM 1’ and ‘PM 2’ curves reduces to wind turbine MTTF of 0.375 years, as compared to the results presented in Figure 6.11, whilst by increasing the cost of vessel hiring to 100,000 pounds, then the intersection point of the ‘PM 1’ and ‘PM 2’ curves increases to wind turbine MTTF of 0.42 years, as compared to the results in Figure 6.11. An interesting point that these results indicate is that as the cost of maintenance vessels increases then the ‘PM 1’ scenario yields lower LPC of energy and consequently would be preferred over the ‘PM 2’ scenario, for larger wind turbine MTTF range.

6.4.4 The effect of the number of failures

Figure 6.15 gives the comparison between the ‘PM 1’ (blue) and PM 2’ (green) scenarios of planned intervention maintenance policy for the Kentish Flats offshore wind farm, where the outputs are presented in terms of the number of wind turbine failures, total cost of maintenance, percentage of maintenance cost in LPC of energy, and percentage of maintenance costs in CAPEX, all plotted against wind turbine MTTF.

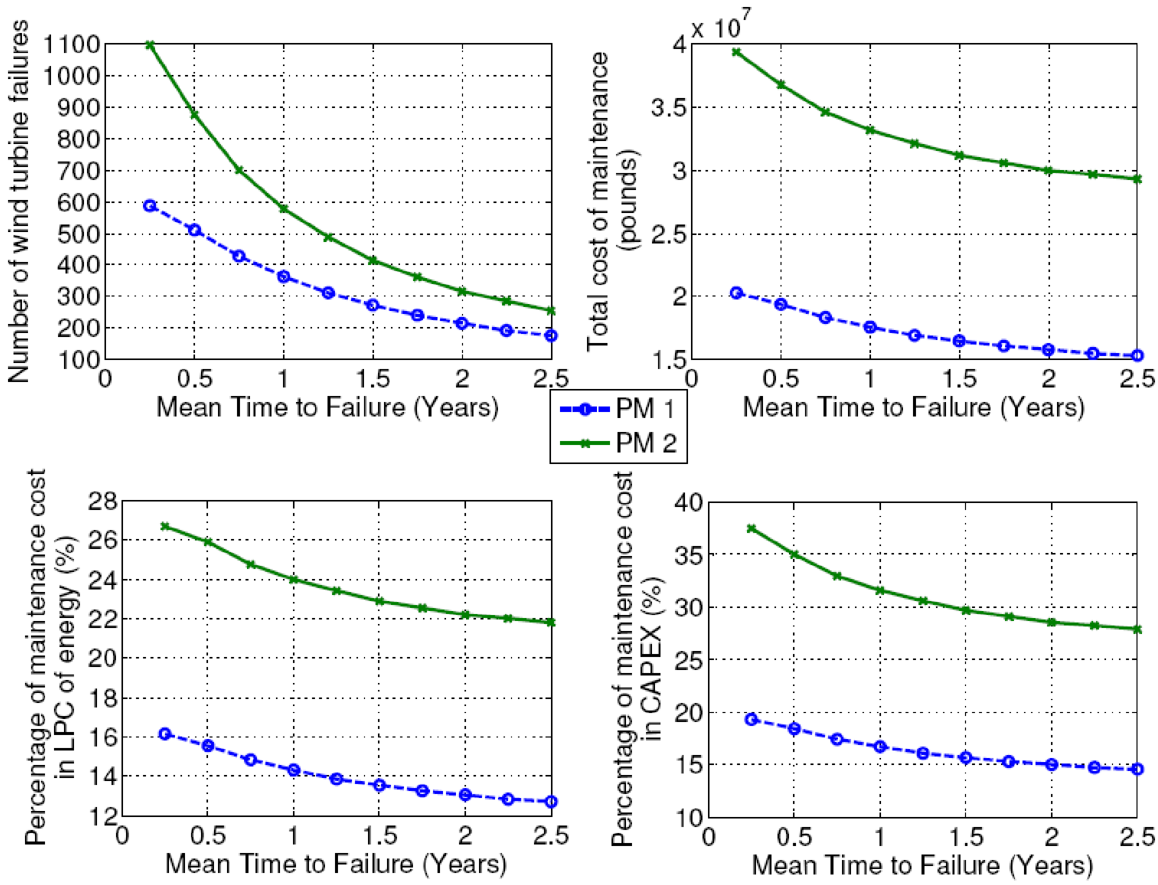

Figure 6.15 The comparison between the planned intervention maintenance strategies, PM1 and PM2, for the Kentish Flats offshore wind farm in terms of number of wind turbine failures, total cost of maintenance, percentage of maintenance cost in LPC of energy and percentage of maintenance cost in CAPEX

Considering the number of wind turbine failures versus wind turbine MTTF, the ‘PM 1’ scenario deals with lower number of failures, as compared to the ‘PM 2’ scenario, this being explained by the fact that for ‘PM 2’ scenario the failed wind turbines are being repaired twice a year. The interesting point to observe in these results is that when employing the ‘PM 1’ scenario the wind turbines that fail between the scheduled maintenance visits remain in a failed mode for longer period, as compared to the ‘PM 2’ scenario, which in turn results in higher energy loss.

Now consider the total cost of maintenance versus wind turbine MTTF in Figure 6.15. The ‘PM 2’ scenario yields higher costs of maintenance as compared to the ‘PM 1’ scenario, this being explained by the higher number of wind turbine failures and consequently higher number of repairs, while also considering the costs incurred for the preventive maintenance of the wind turbines, as previously explained for Figure 6.1 in paragraph 6.2. As the wind turbine MTTF increases the total cost of maintenance for both scenarios decreases, this being a result of lower number of repairs. The significant conclusion reached from these results is that as the wind turbine reliability increases, then the cost of maintenance decreases as would be expected from the economic model previously presented in Chapter 4 (p. 105).

Now consider the percentage of maintenance cost in the LPC of energy versus wind turbine MTTF in Figure 6.15. The percentage of maintenance cost in the LPC of energy represents the OPEX, which is calculated based on equation 4.8, as previously presented for the economic model in Chapter 4 (p. 105). These results can be used for comparing the planned intervention maintenance policy against published data for the corrective maintenance strategy in terms of percentage of maintenance cost in the LPC of energy. For the ‘PM 2’ scenario the cost of maintenance is between 22% and 27% of the LPC of energy, whilst for the ‘PM 1’ scenario was calculated to be between 13% and 16%, this being explained by the higher number of wind turbine failures, as shown in the previous paragraphs. As the wind turbine MTTF increases the difference between the ‘PM 1’ and ‘PM 2’ curves decreases, which indicates that the maintenance cost in the LPC of energy for the ‘PM 2’ scenario decrease significantly, as compared to the ‘PM 1’ scenario. The significant point to observe in these results is that the effect of increasing wind turbine reliability on the 'PM 2' scenario is higher, as compared to the 'PM 1' scenario.

Now consider the percentage of maintenance cost in the CAPEX versus wind turbine MTTF as presented in Figure 6.15. The percentage of maintenance cost in CAPEX was calculated by dividing the OPEX with the CAPEX. These results can be used for comparing the planned intervention maintenance policy against published data for the corrective maintenance strategy in terms of percentage of maintenance cost in CAPEX. For the 'PM 2' scenario the cost of maintenance is between 28% and 37% of the CAPEX, whilst for the 'PM 1' scenario was calculated to be between 15 and 20%, this being explained by the higher number of wind turbine failures, as shown in the previous paragraphs. When comparing the percentage of maintenance cost in the CAPEX with the results obtained from the London Array offshore wind farm, it can be concluded that the percentage of maintenance cost in the CAPEX for the Kentish Flats offshore wind farm is found to be significantly higher, which can be explained by the fact that the cost of each installed wind turbine, i.e. CAPEX divided by the total number of wind turbines in the wind farm, for the London Array is calculated to be 11.2 million pounds per wind turbine and for the Kentish Flats is calculated to be 3.5 million pounds per wind turbine. This indicates that the CAPEX of the Kentish Flats offshore wind farm is significantly lower, as compared to the London Array, as a result of the closer distance to shore and shallower water that the Kentish Flats offshore wind farm has been constructed in.

6.4.5 Discussions on the simulated results for case study 3

The investigations on the planned intervention maintenance policy for the Kentish Flats offshore wind farm indicate that the decision on the preferred maintenance scenario, i.e. 'PM 1' or 'PM 2', depends on a number of input parameters and outputs of the project, e.g. the reliability of the wind turbines, the wind turbine repair time, the capacity factor of the wind farm, the maintenance transportation cost, the energy output and the LPC of energy. For wind turbine reliability levels of MTTF>0.39 the 'PM 1' scenario is preferred as it would yield LPC of energy lower, as compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF higher than 0.39 years then the ‘PM 2’ scenario would be preferred. This observation indicates that for the Beatrice offshore wind farm there is a specific wind turbine reliability level, i.e. MTTF=0.39, upon which the decision on the planned intervention maintenance policy scenario could be based.

The variation in the wind turbine mttr and mtpm could result by the change in wind turbine accessibility levels, due to weather and sea state, or availability of transportation means or availability of spare parts. By varying the wind turbine mttr and mtpm for the Kentish Flats offshore wind farm the results indicate the significance of energy losses during the scheduled maintenance visits. The simulated results also indicate that by varying the wind turbine mttr and mtpm, then the specific wind turbine reliability level, as explained in the previous paragraph, upon which the decision on the planned intervention maintenance policy scenario could be based on, also varies. A significant conclusion reached from these results is that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the ‘PM 2’ scenario. The same conclusions could also be reached when varying the maintenance transportation costs, which could result by the change in the availability of maintenance vessels. The results indicate that as the transportation costs increase then the specific wind turbine reliability, upon which the decision on the planned intervention maintenance policy scenario could be based on, also increases. The results also indicate that as the hiring cost of maintenance vessels increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the ‘PM 2’ scenario.

The change in the capacity factor of the offshore wind farm could indicate a change in the location or the windiness of the location. The interesting point to observe from the results of the comparison between the two planned intervention maintenance policy scenarios is that as the capacity factor increases the ‘PM 2’ scenario would be preferred over the ‘PM 1’ scenario as it achieves lower LPC of energy.

The number of vessels and helicopters required for the servicing of the wind turbines on each scheduled maintenance visit to the Kentish Flats offshore wind farm can be estimated by using the graph for the number of wind turbine failures against wind turbine MTTF as presented in Figure 6.15. For example considering the 'PM 2' scenario as applied to the Kentish Flats offshore wind farm with a wind turbine MTTF of 0.5 years, then by using this graph, the number of wind turbine failures is 900 on average for 20 years of operation or 22 on average for every scheduled maintenance visit. It has been explained in Chapter 3 (p. 131) and Appendix E that the failures associated with large components that require vessels for servicing account for the 25% of all the failures, which means that 5 failures out of the 22 per scheduled maintenance visit would require the use of a vessel. This would mean that these failures could be serviced by hiring one vessel for every scheduled maintenance visit to the Kentish Flats offshore wind farm, by considering the availability of spare parts and the repair time of 1 day per failure. Similarly the number of helicopters required for servicing the failures of the wind turbines for every scheduled maintenance visit, could be calculated. However, it should be considered that further resources, i.e. helicopters, would be required in addition to the ones considered above, for the completion of the preventive maintenance tasks during the scheduled maintenance visits.

Considering the percentage of maintenance costs in the LPC of energy, the 'PM 2' scenario yields significantly higher results across the range of wind turbine MTTF, as compared to the 'PM 1' scenario, but the LPC of energy for the 'PM 2' scenario is lower as compared to the 'PM 1' scenario for wind turbine MTTF>0.39. This indicates that despite the higher maintenance costs observed for the 'PM 2' scenario, the higher energy output that is achieved, as it benefits from higher wind farm availability, results in lower LPC of energy and shows that the 'PM 2' scenario would be preferred over the 'PM 1' scenario for wind turbine MTTF>0.39. On the other hand, for wind turbine MTTF range of $0.25 \leq MTTF \leq 0.39$ the 'PM 1' scenario would be preferred since it achieves higher energy output and lower LPC of energy, as compared to the 'PM 2' scenario, which suffers from higher energy loss due to the fact that 'PM 2' scenario offers twice as many scheduled maintenance visits to the offshore wind farm as compared to the 'PM 1' scenario.

6.5 Comparison of the simulated results between 'PM 1' and 'PM 2' scenarios

Considering the results presented in this Chapter for the different offshore wind farm case studies investigated, then some significant conclusions could be reached on the deployment of different scenarios of the planned intervention maintenance policy:

- Considering prototype projects such as the Beatrice offshore wind farm, then the planned intervention maintenance policy does not present an economically viable solution, since it achieves LPC of energy that is not competitively compared against the results from the other offshore wind farm case studies.

- The selection between the 'PM 1' and the 'PM 2' scenarios of the planned intervention maintenance policy has been concluded to depend heavily on the wind turbine reliability, wind farm capacity and availability of resources for maintenance expeditions. It has also been concluded from the simulated output results that there is a specific wind turbine reliability range for which the 'PM 1' scenario would be preferred over the 'PM 2' scenario, since it achieves lower LPC of energy.

- The wind turbine reliability range mentioned above exists for the lower end of wind turbine MTTF, i.e. $0.25 \leq MTTF \leq 0.35$. The upper limit of this wind turbine MTTF range, i.e. MTTF of 0.35 years, could vary up to 15% depending on the wind farm parameters, e.g. wind turbine repair time, wind turbine power rating, wind farm capacity factor, weather and sea state, availability and cost of maintenance vessels and helicopters, and the availability of spare parts.

- However, for higher wind turbine reliability levels, i.e. MTTF≥0.35 then the 'PM 2' scenario would be preferred over the 'PM 1' scenario, as it yields significantly lower LPC of energy.

The simulated results for the planned intervention maintenance policy for the three case studies; London Array, Beatrice and Kentish Flats offshore wind farms were presented in terms of wind farm availability, cumulative energy output and LPC of energy. These results are summarised in Table 6.4, for comparison purposes, and are divided into two sections for different wind turbine MTTF ranges, i.e. 0.25≤MTTF≤0.5 and 0.5≤MTTF≤1 that represent the reliability of offshore wind turbines, as previously explained in the reliability model in Chapter 4 (p. 96). Each wind turbine MTTF range is also divided into two sub-sections that each give the results for the two planned intervention maintenance policy scenarios that have been investigated in this Chapter, i.e. 'PM 1' and 'PM 2'. Further, Table 6.5 summarises the results of the two future offshore wind farm case studies used in Chapter 5 for the validation of the planned intervention maintenance policy model, i.e. the Opti-Owecs and DOWEC project, which are also presented in Table 6.5 in two sections for the two maintenance scenarios that were investigated, i.e. 'PM 1' and 'PM 2'. The following paragraphs compare the results obtained from the simulation of the planned intervention maintenance policy, as presented in Tables 6.4 and 6.5, between the 'PM 1' and 'PM 2' scenarios in terms of wind farm availability, cumulative energy output and LPC of energy.

Table 6.4 Results from simulating the planned intervention maintenance policy scenarios for the three case studies investigated in Chapter 6

Case study offshore wind farms	Availability (%)				Energy Output (kWh) * 10^9				LPC of energy (pence/kWh)			
Reliability level	**0.25≤MTTF≤0.5**		**0.5≤MTTF≤1**		**0.25≤MTTF≤0.5**		**0.5≤MTTF≤1**		**0.25≤MTTF≤0.5**		**0.5≤MTTF≤1**	
Maintenance Scenario	**PM 1**	**PM 2**	**PM 1**	**PM 2**	**PM 1**	**PM 2**	**PM 1**	**PM 2**	**PM 1**	**PM 2**	**PM 1**	**PM 2**
London Array (Case study 1)	26 - 45	45 - 64	45 - 65	64 - 78	11-21	6.2-29	21-32	29-54	9.8 - 18.9	7.5 - 35	6.5- 9.8	4 - 7.5
Beatrice (Case study 2)	25 - 44	49 - 64	44 - 65	64 - 78	0.14 - 0.26	0.07 - 0.36	0.4 - 0.26	0.78 - 0.36	14 - 27.7	10.7 - 66	9.4 - 14	5.6- 10.7
Kentish Flats (Case study 3)	25 - 44	49 - 65	44 - 65	63 - 78	1.2-2.3	0.7-3.2	2.3-3.5	3.2-6	5.4 - 10.3	4.4 - 21	3.5- 5.4	2.3 -4.4

Table 6.5 Results from simulating the planned intervention maintenance policy scenarios for the two future projects investigated in Chapter 5

Project study from validation in Chapter 5	Availability (%)		Energy Output (kWh) * 10^9		LPC of energy (pence/kWh)	
Maintenance Scenario	**PM 1**	**PM 2**	**PM 1**	**PM 2**	**PM 1**	**PM 2**
Opti–OWECS (**0.56≤MTTF≤0.7**)	46 - 56	65 - 70	9.9	15.9	3.4	2.66
DOWEC (**MTTF = 0.645**)	49 - 55	66 - 70	16.2 – 17.9	26 – 31	2.4 - 3	1.9 – 2.2

6.5.1 Comparison of the wind farm availability

Considering the wind farm availability presented in Tables 6.4 and 6.5, then the results show no significant variation between the different case studies investigated, this being explained by the fact that wind farm availability results from the selection of the planned intervention maintenance policy scenario and the wind turbine MTTF range. When comparing the results obtained from the two scenarios simulated, then the 'PM 2' scenario for a wind turbine MTTF range of $0.25 \leq MTTF \leq 1$ achieves significantly higher wind farm availability, as compared to the 'PM 1' scenario, regardless of the case study investigated, this being explained by the fact that the 'PM 2' scenario simulates twice as many scheduled maintenance visits to the offshore wind farm directly resulting in higher availability levels. A further significant conclusion reached from the results summarised in Tables 6.4 and 6.5 is that as the wind turbine MTTF increases then the difference in wind farm availability between the 'PM 1' and 'PM 2' scenario decreases significantly, this being explained by the increase in wind turbine reliability levels.

However, a significant point of interest is to compare the simulated results of the wind farm availability obtained from the planned intervention maintenance policy against the published results for the corrective maintenance strategy. Considering the accessibility level of existing offshore wind farm, as related to weather and sea state conditions in the North Sea, when employing the corrective maintenance strategy, then the wind farm availability achieved is 75-80%,[72,73,13] whilst for the planned intervention maintenance policy is simulated to be 46-56% for the 'PM 1' scenario and 65-70% for the 'PM 2' scenario (see paragraph 5.2). These results indicate that the corrective maintenance strategy achieves higher wind farm availability, this being explained by the development of the planned intervention maintenance policy, as detailed in Chapter 3, which aims to compromise wind turbine availability levels, by simulating less maintenance expeditions in an attempt to achieve a more competitive price of energy produced.

6.5.2 Comparison of the energy output

Now consider the cumulative energy output for all the case studies investigated, as summarised in Tables 6.4 and 6.5. The results obtained from the simulation of the planned intervention maintenance policy indicate that as the wind turbine MTTF increases then the energy output also increases, this being explained earlier in this Chapter. A significant conclusion reached when comparing the results between the planned intervention maintenance policy scenarios, is that for low wind turbine reliability levels, i.e. $0.25 \leq \text{MTTF} \leq 0.35$, the 'PM 1' scenario yields higher energy output, as compared to the 'PM 2' scenario, this being explained by the effect of the period selected for the wind farm maintenance expeditions to take place, when considering the energy losses during the scheduled maintenance visits in relation to low reliability levels.

Considering the 'PM 1' scenario, the scheduled maintenance visits are planned during July, where the energy losses for repairs and preventive maintenance would account for a maximum of 5.8% of the total energy output over the operational year, as discussed earlier when explaining the energy model in Chapter 4 (p. 110), whilst considering the 'PM 2' scenario, the scheduled maintenance visits are planned twice a year, during October and May, where the energy losses for repairs and preventive maintenance would account for a maximum of 15.9% (8.8% for October and 7.1% for May) of the total energy output for the operational year, also explained earlier in Chapter 4. The results obtained indicate that as the wind turbine MTTF decreases then more wind turbines will fail during the year, so the cumulative repair time for all the wind turbines in the offshore wind farm increases, which in turn results in higher energy losses for the 'PM 2' scenario, as compared to the 'PM 1' scenario. It should also be considered that the proactive nature of the planned intervention maintenance policy, as previously explained in Chapter 3, would require preventive maintenance tasks to take place on all the wind turbines, which in turn results in the wind turbines to stop operation for the maintenance work to take place. This practice, which is identified in Chapter 3 as a main disadvantage of planned intervention maintenance policy, is performed twice as many times for the 'PM 2' scenario as compared to 'PM 1', which in turn results in higher energy loss.

However, when considering higher wind turbine reliability levels, i.e. $0.35 \leq MTTF \leq 1$, then the 'PM 2' scenario achieves significantly higher energy output, regardless of the case study investigated, as compared to the 'PM 1' scenario, this being explained by the lower number of failures resulting in lower energy losses during the scheduled maintenance visits.

A significant conclusion reached from the comparison of the energy output results between the different case studies investigated, as summarised in Tables 6.4 and 6.5, is that as the number of wind turbines in a wind farm decreases then the energy output also decreases, which in turn affects significantly the cost of energy produced, which was also expected from the background theory detailed for the energy model in Chapter 4 (p. 110).

6.5.3 Comparison of the LPC of energy

Now consider the LPC of energy for all the case studies investigated, as summarised in Tables 6.4 and 6.5. The results obtained from the simulation of the planned intervention maintenance policy indicate that as the wind turbine MTTF increases the LPC of energy decreases, this being explained by the lower maintenance costs and higher energy harness achieved, as explained in the previous paragraphs. A significant conclusion reached when comparing the results between the planned intervention maintenance policy scenarios, is that for low wind turbine reliability levels, i.e. $0.25 \leq MTTF \leq 0.35$, the 'PM 1' scenario yields lower LPC of energy, as compared to the 'PM 2' scenario, this being explained by the effect of the period selected for the wind farm maintenance expeditions to take place, when considering the energy losses during the scheduled maintenance visits and the higher maintenance costs incurred, as explained in the previous paragraphs.

However, when considering higher wind turbine reliability levels, i.e. $0.35 \leq MTTF \leq 1$, then the 'PM 2' scenario achieves significantly lower LPC of energy, regardless of the case study investigated, as compared to the 'PM 1' scenario, this being explained by the higher energy harness, as detailed in the previous paragraph and the lower maintenance costs for repairs.

Now when comparing the results between the different case studies investigated, as summarised in Table 6.4, it can be observed that the Beatrice offshore wind farm achieves the highest LPC of energy, which indicates that the energy produced is not competitive as compared to the other case studies investigated, this being explained by the prototype nature of the Beatrice offshore wind farm that indicates the very low number of wind turbines in the wind farm and the significantly higher cost per installed wind turbine. Now consider the comparison of the LPC of energy between the London Array and the Kentish Flats offshore wind farms, where the results indicate that the Kentish Flats achieves lower LPC of energy, this being a direct result of the difference in the CAPEX of each project. The Kentish Flats is an offshore wind farm located closer to shore (25 km) and at shallower waters, which decreases the cost of wind turbine foundations, cables, and installation process, which account for around 40% of the CAPEX,[72,73] as compared to the London Array offshore wind farm. This could also be observed by dividing the CAPEX of each case study with the total number of wind turbines in the wind farm to calculate the cost per installed wind turbine. For the Beatrice offshore wind farm it is calculated to be 17.5 million pounds per wind turbine installed, for the London Array offshore wind farm is calculated to be 11.2 million pounds and for the Kentish Flats is 3.5 million pounds per wind turbine installed. These results point out the significant effect of the distance to shore and the water depth on the LPC of energy of offshore wind farms.

However, when comparing the results of the Kentish Flats case study against the results obtained from the DOWEC project in Tables 6.4 and 6.5, the results indicate that the DOWEC project yields significantly lower LPC of energy, despite the fact that it has a considerably higher calculated cost per installed wind turbine, i.e. 5.84 million pounds. This could be explained by the fact that the DOWEC project achieves significantly higher energy output, as compared to the Kentish Flats, since each wind turbine has twice the power rating of those installed in the Kentish Flats. The significant conclusion reached from the observation of these results is that the wind turbine power rating has a higher effect on the LPC of energy than the distance to shore and the water depth, as discussed in the previous paragraph.

6.6 Comparison of the simulated results against published data

Table 6.6 gives a summary from a number of different sources on hard data of LPC of energy on operational but also future development of offshore wind farms, which employ the corrective maintenance strategy, i.e. the Concerted Action on Offshore Wind Energy in Europe (CAOWEE),[9] the Renewable Energy Burden Sharing (REBUS),[96] the Impact of Banding the Renewables Obligation – Cost of electricity production (IBRO) study,[35] the Royal Academy of Engineering (RAE),[97] the European Wind Energy Association (EWEA),[61,62] and the British Wind Energy Association (BWEA).[8,98] The published data on future offshore wind farms from the Opti-Owecs and the DOWEC project have also been considered, as shown in Table 6.6, which are used to compare the simulated output results obtained by applying the planned intervention maintenance policy on the different case studies investigated in this Chapter against the corrective maintenance strategy.

The Concerted Action on Offshore Wind Energy in Europe (CAOWEE) is a project supported by the European Commission and was finalised in 2001.[9] The objective of the project was to define the current state-of-the-art of offshore wind energy in Europe by gathering and evaluating information from different offshore wind farms and by publishing the results. The values of LPC of energy that are reported in this project are real industrial data from existing offshore wind farms that are operational in Europe, and more specifically the Vindeby and Lely offshore wind farms, which are prototype projects that were built in the early 1990s and consist of a limited number of wind turbines, while the Tuno Knob and Blyth projects were commissioned in recent years and represent typical existing offshore wind farms. Further details on these offshore wind farms are presented in Appendix B.2.

Table 6.6 LPC of energy from published sources. The data reflect the use of corrective maintenance strategy.[9, 96, 35, 97, 61,62,8, 98]

Reference project	LPC of energy (p/kWh)
CAOWEE project	
Vindeby offshore wind farm in Denmark (operational)	5.86
Lely offshore wind farm in Netherlands (operational)	5.93 – 9.44
Tuno Knob offshore wind farm in Denmark (operational)	4.55 – 5.63
Blyth offshore wind farm in the UK (operational)	4.82 – 5.51
REBUS for offshore wind farms in the EU	
Low wind conditions (6-7 m/s)	9.41 – 9.71
Medium wind conditions (7-9 m/s)	4.56 – 6.91
High wind conditions (>9 m/s)	3.99 - 6
IBRO (DTI) (White Paper accompanying report)	8.1 – 10.1
Royal Academy of Engineering (RAE)	5.5 – 7.21
European Wind Energy Association (EWEA)	4.7
British Wind Energy Association (BWEA)	3.82 – 4.97
Opti – OWECS project	3
DOWEC project	2.3

The Renewable Energy Burden Sharing (REBUS) study was financially supported by the European Commission, in the fifth framework programme of the 'Directorate Research' and was finalised in 2001.[96] This project provides insights of the effects of implementing targets for renewable electricity generation at EU Member State level and the impact of introducing burden sharing systems within the EU. The values of LPC of energy that are reported in this project reflect real industrial data from existing offshore wind farms in the EU, for different wind conditions, i.e. different capacity factors. The studies from the RAE, EWEA and BWEA presented in Table 6.6 also report on LPC of energy from existing operational offshore wind farms for different locations and different capacity factors.

The Impact of Banding the Renewables Obligation – Cost of electricity production (IBRO) is a report issued by the Department of Trade and Industry (DTI) to accompany the Energy White Paper, and was finalised in 2007.[35] The main objective of this report was to estimate the LPC of energy for a number of renewable technologies in Europe and especially the UK. Ranges of LPC of energy have been calculated for future offshore wind farms based on current costs, which were deflated based on major cost drivers, i.e. capacity factors and the estimated future wind farm capacity, for Round Two offshore development, e.g. the London Array offshore wind farm, when employing the corrective maintenance strategy.

6.6.1 Comparison of the results for prototype (small) offshore wind farms

Now consider the simulated output results in terms of LPC of energy from the Beatrice offshore wind farm, as shown in Table 6.4, when employing the planned intervention maintenance policy. These results are compared against the published data of other prototype offshore wind farms which use the corrective maintenance strategy, i.e. the Vindeby and Lely offshore wind farms from the CAOWEE project, as shown in Table 6.6. Considering the wind turbine MTTF range of $0.25 \leq MTTF \leq 1$, then the results in terms of LPC of energy when simulating the planned intervention maintenance policy are found to be higher for both the 'PM 1' and 'PM 2' scenarios, as compared against the corrective maintenance strategy results, in Table 6.6, which indicates that the planned intervention maintenance policy would not be an economically viable solution for prototype offshore wind farms and therefore the current maintenance practices should be considered.

6.6.2 Comparison of the results for existing (medium size) offshore wind farms

Now consider the results in terms of LPC of energy from the Kentish Flats offshore wind farm, as shown in Table 6.4, when simulating the planned intervention maintenance policy. These output results are compared against the published data for existing (medium size) offshore wind farms, which employ the corrective maintenance strategy, e.g. the Tuno Knob and Blyth offshore wind farms from the CAOWEE project, the REBUS project, the EWEA, the BWEA, and the RAE, as shown in Table 6.6. Considering the wind turbine MTTF range of 0.25≤MTTF≤0.5, then the results in terms of LPC of energy simulating the planned intervention maintenance policy are found to be higher, as compared against the corrective maintenance strategy data, which indicates that the planned intervention maintenance policy would not be an economically viable solution for medium size offshore wind farms located close to shore with small number of wind turbines, and therefore the current maintenance practices should be considered.

However, when considering the wind turbine MTTF range of 0.35≤MTTF≤1, then the simulated results in terms of LPC of energy when employing the 'PM 2' scenario of the planned intervention maintenance policy for the existing offshore wind farms, are found to be directly comparable against the published data employing the corrective maintenance strategy, while in some cases are found to be even lower, e.g. as compared against the REBUS project and RAE results. The significance of this conclusion indicates that when the wind turbine reliability levels increase then the planned intervention maintenance policy tends to achieve LPC of energy that is competitive against the corrective maintenance strategy for existing offshore wind farms, and therefore the planned intervention maintenance policy could also be considered as an economically viable substitution to the current maintenance practices.

6.6.3 Comparison of the results for near future (large) offshore wind farms

Now consider the simulated output results in terms of LPC of energy from the London Array offshore wind farm, as shown in Table 6.4, when employing the planned intervention maintenance policy. These output results are compared against the published data for near future (large) offshore wind farms, which employ the corrective maintenance strategy, i.e. the IBRO project, as shown in Table 6.6. Considering the wind turbine MTTF range of 0.25≤MTTF≤0.5, then the results in terms of LPC of energy simulating the planned intervention maintenance policy are found to be higher, as compared against the corrective maintenance strategy published data, which indicates that the planned intervention maintenance policy would not be presenting an economically viable solution for near future offshore wind farms consisted of wind turbines with significantly low reliability.

However, when considering the wind turbine MTTF range of 0.5≤MTTF≤1, then the results in terms of LPC of energy that both the ‘PM 1’ and ‘PM 2’ scenarios of the planned intervention maintenance policy achieved, are found to be significantly lower, as compared against the published data for the corrective maintenance strategy, which indicates that when the wind turbine reliability levels increase then the planned intervention maintenance policy could yield results in terms of LPC of energy that are significantly lower for near future offshore wind farms, and therefore the planned intervention maintenance policy should be preferred over the current maintenance strategies.

6.6.4 Comparison of the results for futuristic (very large) offshore wind farms

Now consider the results in terms of LPC of energy obtained from the Opti-OWECS and DOWEC offshore wind farms, as shown in Table 6.4, when simulating the planned intervention maintenance policy. These simulated output results are compared against the published data of future (very large) offshore wind farms, which employ the corrective maintenance strategy, as shown in Table 6.6. Considering the ‘PM 1’ scenario of the planned intervention maintenance policy across the range of wind turbine MTTF, the simulated results in terms of LPC of energy are found to be higher, as compared against the published data for the corrective maintenance strategy, which indicates that the use of ‘PM 1’ scenario is not found to be an economically viable solution for the future offshore wind farms, when considering the current reliability levels of offshore wind turbines.

However, when considering the ‘PM 2’ scenario of the planned intervention maintenance policy then the simulated results in terms of LPC of energy are found to be significantly lower across the range of wind turbine reliability that has been investigated, as compared against the published data for the corrective maintenance strategy. The significant conclusion reached from the observation of these results is that for future large offshore wind farms located far from shore and consisted of high numbers of wind turbine with multiples of the current wind turbine power rating, then the employment of the planned intervention maintenance policy has the potential to become a more economical solution as compared against the corrective maintenance strategy and should therefore be preferred.

6.7 The CO2 emissions from offshore wind farms

Renewable energy projects have met a growing interest in the recent years. After the oil crises in the 1970s and 1980s, which led to a significant increase of the price of the oil, a large number of countries around the world have invested in alternative energy projects and primarily renewable sources to reduce their dependency on oil.[7,98,99,101]

Furthermore, the development of renewable energy project and especially wind energy has been further stimulated during the last 20 years by the Kyoto protocols that many countries in the world have agreed to follow. This agreement involved the reduction of the green house gasses such as CO_2, SO_2 and NO_x, which are emitted from the production of energy from conventional power plants, in order to address global warming issues.[7,101,61,62] The EU member states have agreed to a directive to reduce their CO2 emissions levels by 30%, while also develop at least 20% of their energy produced from renewable energy sources by 2020.[7,8,14] In that respect, offshore wind farms have been employed by a number of European countries to substitute a percentage of energy produced by other conventional power stations aiming to reduce the CO2 emissions.[7,8,14] It becomes interesting after the above observations to investigate what is the contribution of the offshore wind farms to the green house gasses and whether these renewable energy projects are as emissions-free as their operators claim.

The CO2 emissions from offshore wind farms are not just a product of their manufacturing, installation and decommissioning, but also the operation and maintenance of the wind farm during its lifetime has a significant contribution to the emissions of the greenhouse gasses, as explained in chapter 2. This chapter has set out an investigation to determine the level of the CO2 emissions from offshore wind farms due to the operation and maintenance of the wind turbines, and identify which parameters of the wind farm affect the levels of CO2 emissions. Computer based models have been developed to compare and examine the CO2 emissions for the corrective maintenance strategy and the planned intervention maintenance policy for different case studies. The methodology used and the development of the algorithms are explained in the following paragraphs.

6.8 Methodology and algorithm development

In order to compare the CO2 emissions of offshore wind farms due to maintenance expeditions between the planned intervention maintenance policy and the corrective maintenance strategy, computer aided simulation programs were developed to simulate the maintenance expeditions. The programs to simulate the planned intervention maintenance policy have been presented in Chapter 4, whilst the program for the corrective maintenance strategy are presented and verified in the following paragraphs.

The computer simulation program for the corrective maintenance strategy has been developed for the calculation of the CO2 emissions from vessels and helicopters for the maintenance expeditions, presented in Appendix L. The calculation of the CO2 emissions is performed on a kilometre - travelled basis, as presented in Appendix I. The aim of the computer simulations program for the corrective maintenance strategy is to calculate the number of maintenance expeditions to the offshore wind farm by allowing the required stochastic behaviour of the wind turbine time to failure and time to repair. The corrective maintenance strategy CO2 program follows the methodology used for the algorithms developed in the previous chapters for the planned intervention maintenance policy. In that respect, the Monte Carlo method is used to simulate the variability in the failure rates of wind turbines, as has been previously presented for the Monte Carlo model in Chapter 4 (p. 114). The different steps followed for the implementation of the Monte Carlo modelling were:

- To isolate key input variables of the statistical process for modelling,
- Associate a probability distribution for each input variable,
- Produce a large number of random values for these variables, in respect to the probability distribution equation,

- Store the output results of the model from each simulation, and
- Evaluate the outputs by statistical observation.

A mathematical representation of the sequence of steps described above has taken the following form:[88,90]

Let k_1, k_2,… k_n be a set of n independent random variable samples of the key variable. Then let $f(k_i)$, i = 1, 2,…, n be the function of k. By considering the above, the estimation of the mean $\tilde{f}_n$ of the calculated value is presented in the following equation:

$$\tilde{f}_n = \frac{1}{n}\sum_{i=1}^{n} f(k_i) \tag{6.1}$$

When considering the Monte Carlo method applied to the corrective maintenance strategy of offshore wind farms then the system which includes the maintenance process corresponds to the model, whilst the key input variables of the model correspond to the items of the system.[88] In that respect an appropriate way to model the system is a network of items which have different states (operational, failed or undergoing repair), as shown in Figure 6.16.

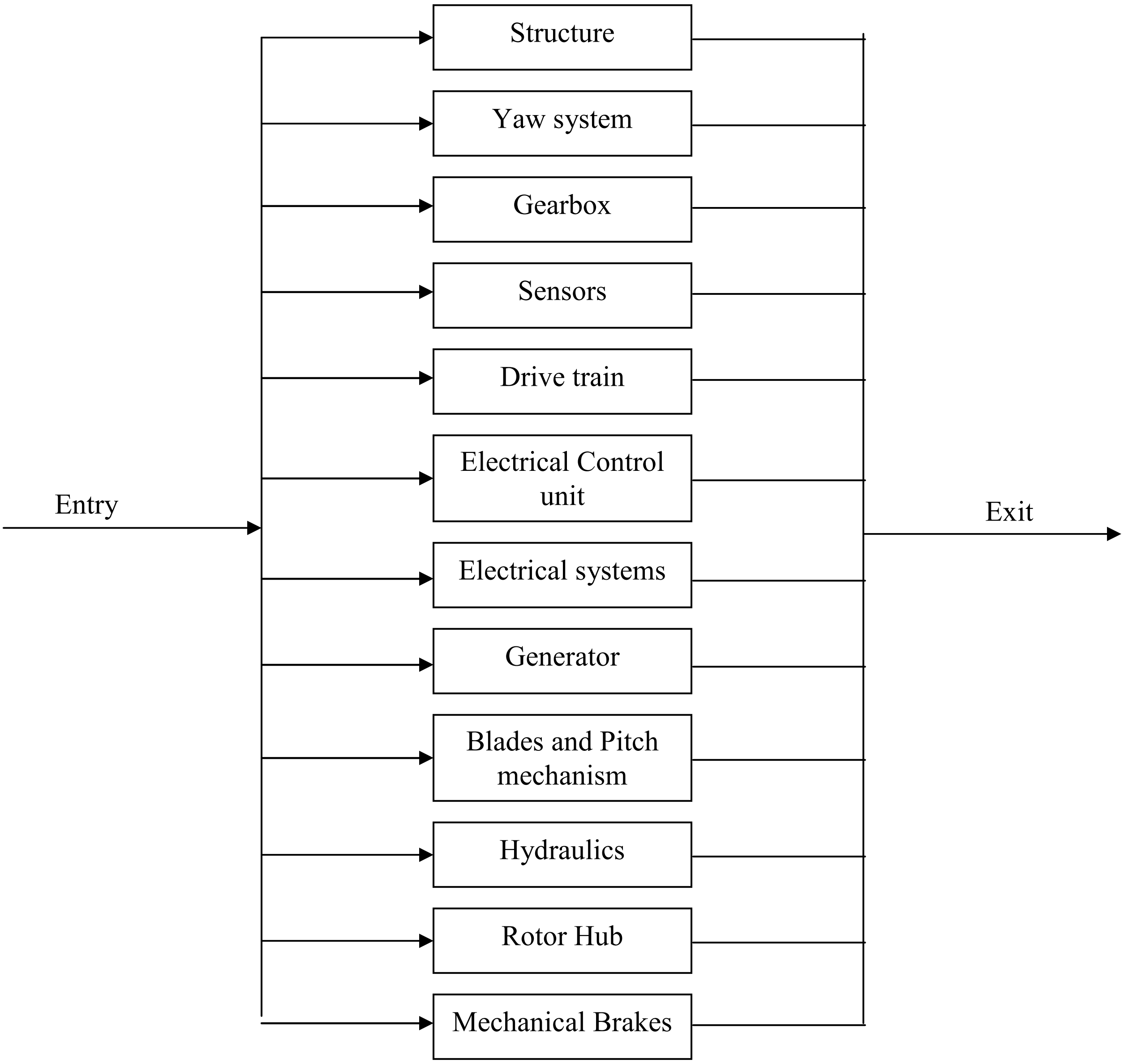

Figure 6.16 Network structure of a modelled offshore wind turbine for the corrective maintenance strategy

When considering the corrective maintenance strategy, every item that fails from the network of items that is shown in Figure 6.16, the wind turbine stops producing wind energy and a maintenance expedition is initiated. The weather and sea state have been simulated in the computer program through the use of accessibility levels, in the same way as has been reported in the Opti-Owecs and DOWEC projects.[70,71,72,73] When 100% of accessibility is simulated for an offshore wind farm then the maintenance expeditions can be performed without any delay, and directly after a wind turbine failure has been identified. The reported accessibility level of existing offshore wind farms in the North Sea, which is directly related to the variability of the weather and sea state, is between 75 and 80%.[70,71,72,73] This indicates that the offshore wind farms employing a corrective maintenance strategy are only accessible 75-80% of the time for repairs and maintenance. This accessibility level is defined as the wind farm availability and is considered as an input parameter for the corrective maintenance strategy CO2 program. The aim of the developed program is to maintain this level of wind farm availability for the duration of the project by increasing the number of maintenance expeditions, as compared to the planned intervention maintenance policy.

The structure of the computer simulation program developed for the corrective maintenance strategy for offshore wind farms is presented in Figure 6.17. The computer simulation program uses four loops one within the other in the same way as for the planned intervention maintenance policy programs, as previously presented in Chapter 4. The first step is for the user to define the input parameters of the offshore wind farm, which are the same as shown in Figure 3.4 in Chapter 3 (p. 86). The following steps are identical with the process that has been explained in Chapter 4 for the planned intervention maintenance policy, only that the repair expeditions take place at any time that a failure has been identified, as explained in the previous paragraph, which is simulated at the ‘Wind turbine loop’ (yellow loop), as shown in Figure 6.17. The output of the computer program for the corrective maintenance strategy is the number of maintenance visits to the offshore wind farm for repairs and preventive maintenance, which is then used to calculate the CO2 emissions.

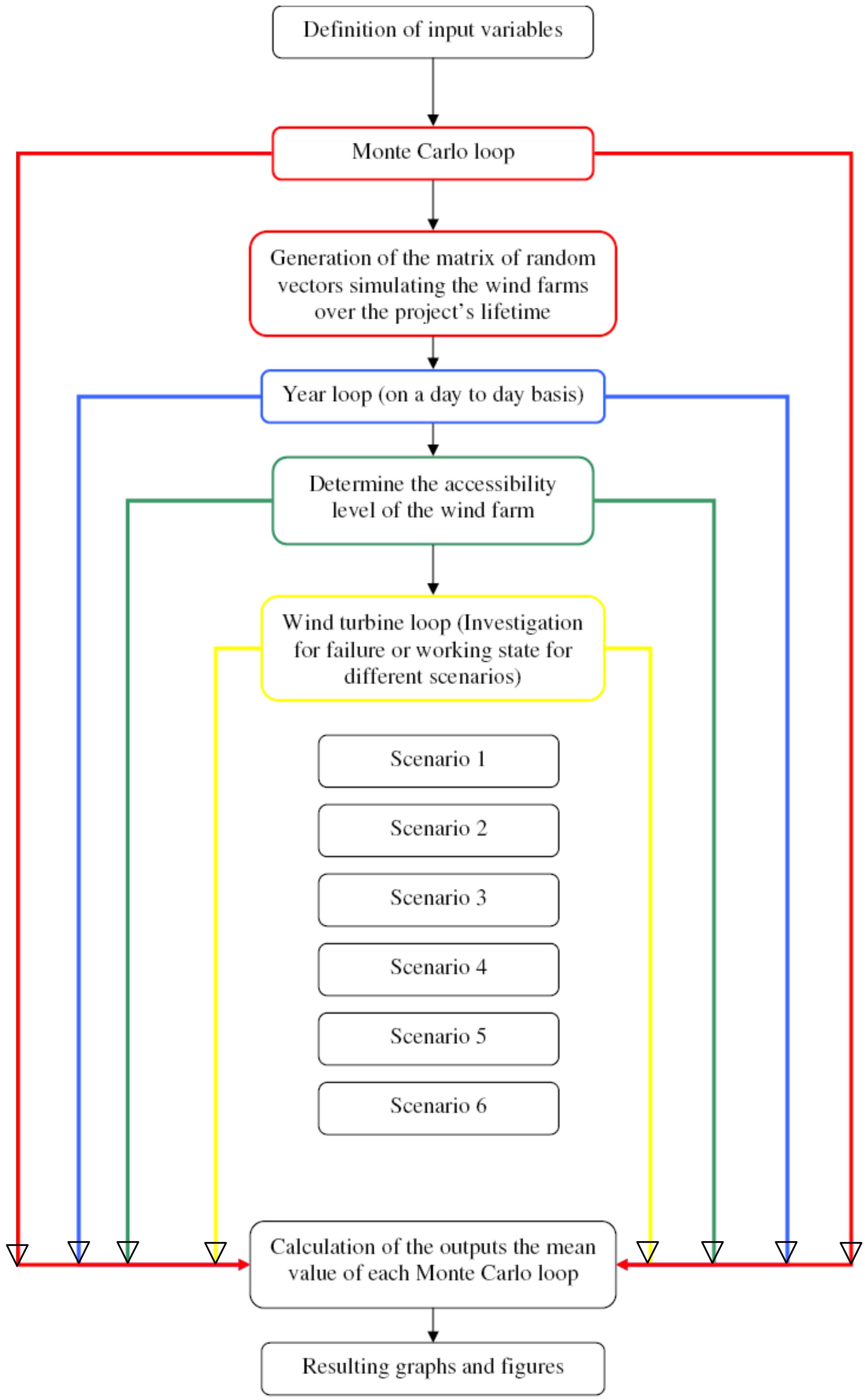

Figure 6.17 Structure of the computer simulation program for corrective maintenance strategy

Considering the 'Wind turbine loop' each wind turbine can possibly go through one of the six different operating states, as presented in Table 6.7. The developed program checks if the wind turbine is in operating state (event 1) or an expedition is required due to failure or preventive maintenance (events 2 to 6). The preventive maintenance is simulated once a year for all the wind turbines in the wind farm, as reported in the Opti-Owecs and DOWEC projects.[70,71,72,73]

The selection of transportation means for the maintenance of the wind turbines is simulated in the same way as for the planned intervention maintenance policy, as previously presented in Chapter 4. Table 6.8 shows the different wind turbine items and the associated transportation means, i.e. vessel or helicopter, which have been assigned based on the size and weight of the item. The components that are repaired by vessels are due to the necessity of a crane. The preventive maintenance and the repair of smaller components are performed by the use of helicopters.

Table 6.7 The different states – events of the wind turbine

State – Event	Description
1	The wind turbine is in an operating state
2	The turbine has a failure and it is waiting for the next available vessel for maintenance
3	The turbine has a failure and it is waiting for the next available helicopter for maintenance
4	The turbine undergoes repair or maintenance with a vessel
5	The turbine undergoes repair or maintenance with a helicopter
6	The turbine undergoes preventive maintenance with a helicopter

Table 6.8 Transportation means for the maintenance or repair of offshore wind turbine components

Transport means	Component maintenance
Vessels	Structure (nacelle, tower, foundations), Gearbox, Generator, Blades, Rotor
Helicopters	Sensors, Yaw system, Electrical Control unit, Hydraulics, Mechanical Brakes, Electrical systems

6.9 Verification of the reactive response CO2 program

The purpose of the verification of the corrective maintenance strategy CO2 program was to carry out a sensitivity analysis to give added confidence to the produced output results. The verification of the computer programs developed to simulate the corrective maintenance strategy CO2 emissions was achieved by using the same established baseline offshore wind farm as in Chapter 5 for the verification of the planned intervention maintenance policy program. All the input parameters that affect the CO2 emissions of the corrective maintenance strategy model are varied through a range of values in order to investigate how the model reacts.

6.9.1 Establishment of baseline

The offshore wind farm that represents the baseline of this study is the London Array offshore wind farm, located 46 km off the coast of Kent and Essex in the UK. London Array has been chosen because it represents a near future large offshore wind farm, currently under construction. The details of the London Array offshore wind farm are presented in Table 6.9 below:[92]

Table 6.9 The parameters of the baseline London Array offshore wind farm.[92]

Parameters	**Value**
Turbine Power rating	3.6 MW
Number of Turbines	175
Distance to shore	46 km
Economic lifetime of project	20 years
Capacity factor	45 %
Wind farm availability	75-80%
Vessel CO2 emissions per km travelled	120,000 grams
Helicopter CO2 emissions per km travelled	31,200 grams
Preventive maintenance period	Once a year

6.9.2 The effect of the distance to shore

Figure 6.18 shows the effect of varying the distance to shore of the offshore wind farm on the number of vessel journeys, the total CO2 emissions due to maintenance expeditions and on the ratio of CO2 emissions to the energy output, all plotted against the wind turbine MTTF. The ratio of CO2 emissions to the energy output has been calculated as it represents the main comparison method between different maintenance strategies and also different energy generation projects in terms of CO2 emissions. Three different values for the distance to shore have been investigated; 46 km (blue), 100 km (green), and 200 km (red). The reliability of the wind turbines is varied between 0.25 and 1 in terms of MTTF in years, as seen on the x-axis of Figure 6.18.

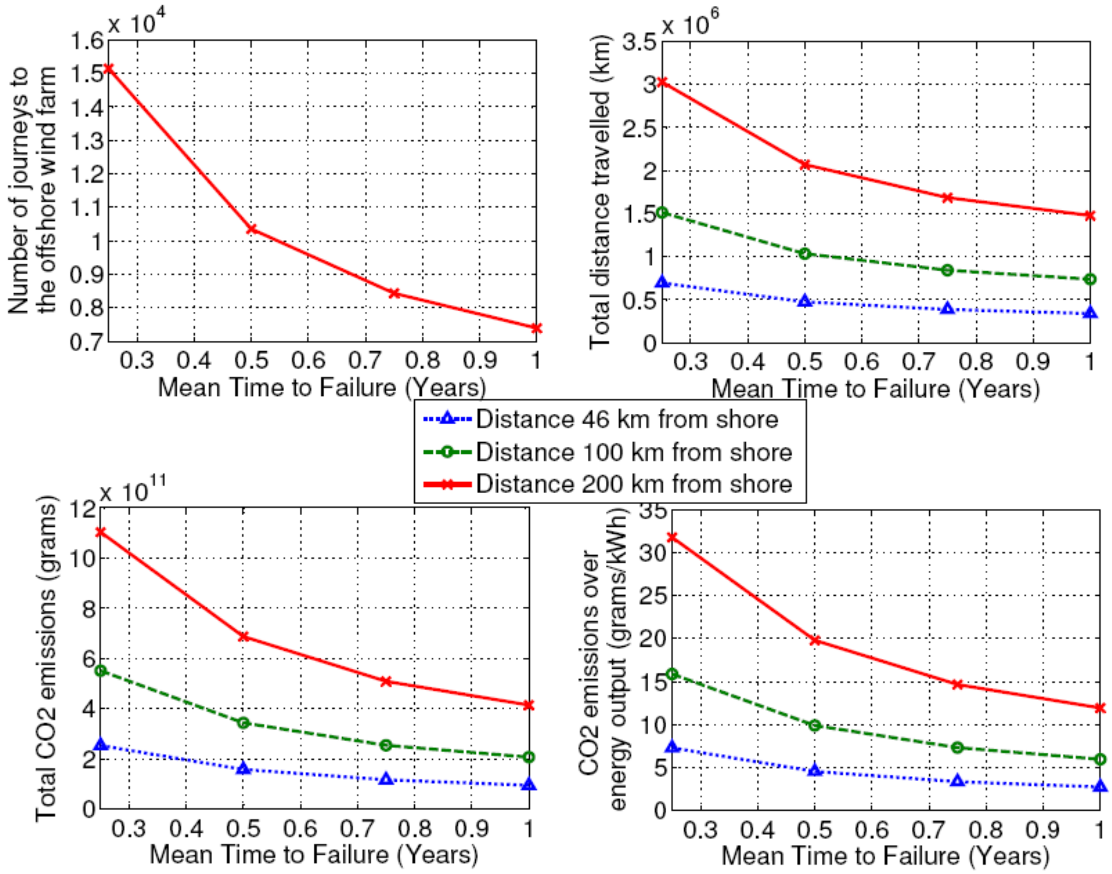

Figure 6.18 The effect of the distance to shore of the offshore wind farm on the number of vessel journeys, the total distance travelled by vessels, the total CO2 emissions and the ratio of CO2 emissions to the energy output. The simulated results are based on the London Array offshore wind farm employing the corrective maintenance strategy.

Considering the number of vessel journeys to the offshore wind farm against the wind turbine MTTF in Figure 6.18, it can be observed that the number of vessel journeys to the offshore wind farm is the same for the three values of the distance used, which indicates that there is no dependency between the two parameters, as would be expected from the equation presented in Appendix I. The number of vessel journeys to the offshore wind farm reduces as the wind turbine MTTF increases, as would be expected, this being explained by the fact that the number of vessel journeys to the offshore wind farm represents the number of wind turbine failures, which in turn decrease as the wind turbine reliability increases. The curve that represents the number of vessel journeys versus the wind turbine MTTF is of a hyperbolic nature (rectangular hyperbola), this being explained by the fact that the relationship between the number of wind turbine failures has a linear relationship with the MTTR of the wind turbines, which in turn is inversed proportional to the wind farm availability, as shown in equation 4.12 previously presented in the Monte Carlo model in Chapter 4 (p. 96).

Now consider the total distance travelled by the vessels versus the wind turbine MTTF in Figure 6.18, where it can be observed that the total distance travelled reduces as the wind turbine MTTF increases, this being explained by the decrease in the number of journeys to the offshore wind farm, as detailed in the previous paragraph. The total distance travelled versus wind turbine MTTF is a curve of hyperbolic nature (rectangular hyperbola), since the relationship between the total distance travelled and the number of journeys to the offshore wind farm is linear, consequently, the relationship between wind turbine MTTF and total distance to shore also becomes inversed proportional, as explained in the previous paragraph. Considering the increase of the distance to shore in Figure 6.18, it can be observed that the total distance travelled by the maintenance transportation also increases, as would be expected from the equation presented in Appendix I.

Now consider the total CO2 emissions versus the wind turbine MTTF in Figure 6.18, where it can be observed that the total CO2 emissions reduce as the wind turbine MTTF increases, this being explained by the decrease in the number of journeys to the offshore wind farm. The curve of the CO2 emissions versus wind turbine MTTF is of hyperbolic nature (rectangular hyperbola), since the relationship between the CO2 emissions and the number of journeys to the offshore wind farm is linear, as presented in the equations of Appendix I. Consequently, the curve between wind turbine MTTF and CO2 emissions also becomes inversed proportional, as explained in the previous paragraph. Considering the increase of the distance to shore in Figure 6.18, it can be observed that the total CO2 emissions by the maintenance vessels also increases, as would be expected from the equation presented in Appendix I.

Now consider the ratio of CO2 emissions to the energy output versus the wind turbine MTTF in Figure 6.18, where it can be observed that the ratio of CO2 emissions to the energy output reduces as the wind turbine MTTF increases, this being explained by the decrease in the number of journeys to the offshore wind farm. The curve of the ratio of the CO2 emissions to the energy output versus wind turbine MTTF is of hyperbolic nature (rectangular hyperbola), this being explained by the fact that the energy output is not affected by the change in the distance to shore and the relationship between the CO2 emissions and the number of journeys to the offshore wind farm is linear, as explained in the previous paragraph, consequently the curve between wind turbine MTTF and the ratio of CO2 emissions to the energy output also becomes inversed proportional. Considering the increase of the distance to shore in Figure 6.18, it can be observed that the ratio of CO2 emissions to the energy output from vessels also increases, as would be expected from the equation presented in Appendix I.

6.9.3 The effect of the capacity factor

Figure 6.19 shows the effect of varying the capacity factor of the offshore wind farm on the total CO2 emissions and the ratio of the CO2 emissions on the energy output, all plotted against wind turbine MTTF. Four different capacity factors have been used for the investigation; 15% (red), 25% (green), 35% (blue) and 45% (black).

Considering the total CO2 emissions versus the wind turbine MTTF in Figure 6.19, it can be observed that the total CO2 emissions are not affected by the change in the capacity factor since there is no relationship between the two parameters, as would be expected from the equation presented in Appendix I. Now consider the ratio of CO2 emissions to the energy output versus the wind turbine MTTF, it can be observed that the ratio of CO2 emissions to the energy output increases as the capacity factor decreases, this being explained by the fact that the energy output is decreasing with decreasing capacity factor, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4 (p. 110).

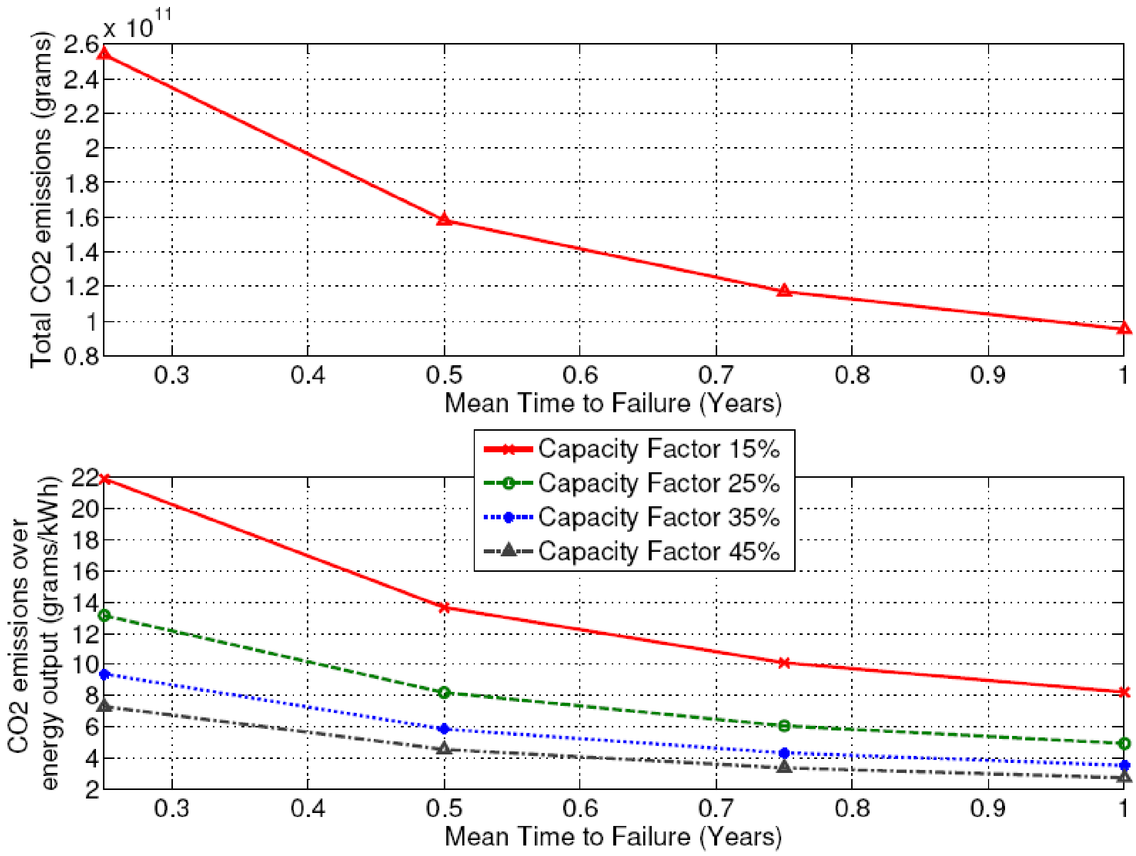

Figure 6.19 The effect of the capacity factor on the CO2 emissions and the ratio of CO2 emissions to the energy output. The simulated results are based on the London Array offshore wind farm employing the corrective maintenance strategy.

6.9.4 The effect of wind turbine power rating

Figure 6.20 shows the effect of varying the wind turbine power rating on the total CO2 emissions and the ratio of the CO2 emissions on the energy output, all plotted against wind turbine MTTF. Three different wind turbine power ratings have been used for the investigation; 1 MW (red), 2 MW (green) and 3 MW (blue). Considering the total CO2 emissions against the wind turbine MTTF in Figure 6.20, it can be observed that the total CO2 emissions are not affected by the change in the wind turbine power rating, since there is no relationship between the two parameters. Now consider the ratio of CO2 emissions to the energy output against the wind turbine MTTF, it can be observed that the ratio of CO2 emissions to the energy output increases as the wind turbine power rating decreases, this being explained by the fact that the energy output decreases with decreasing wind turbine power rating, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4.

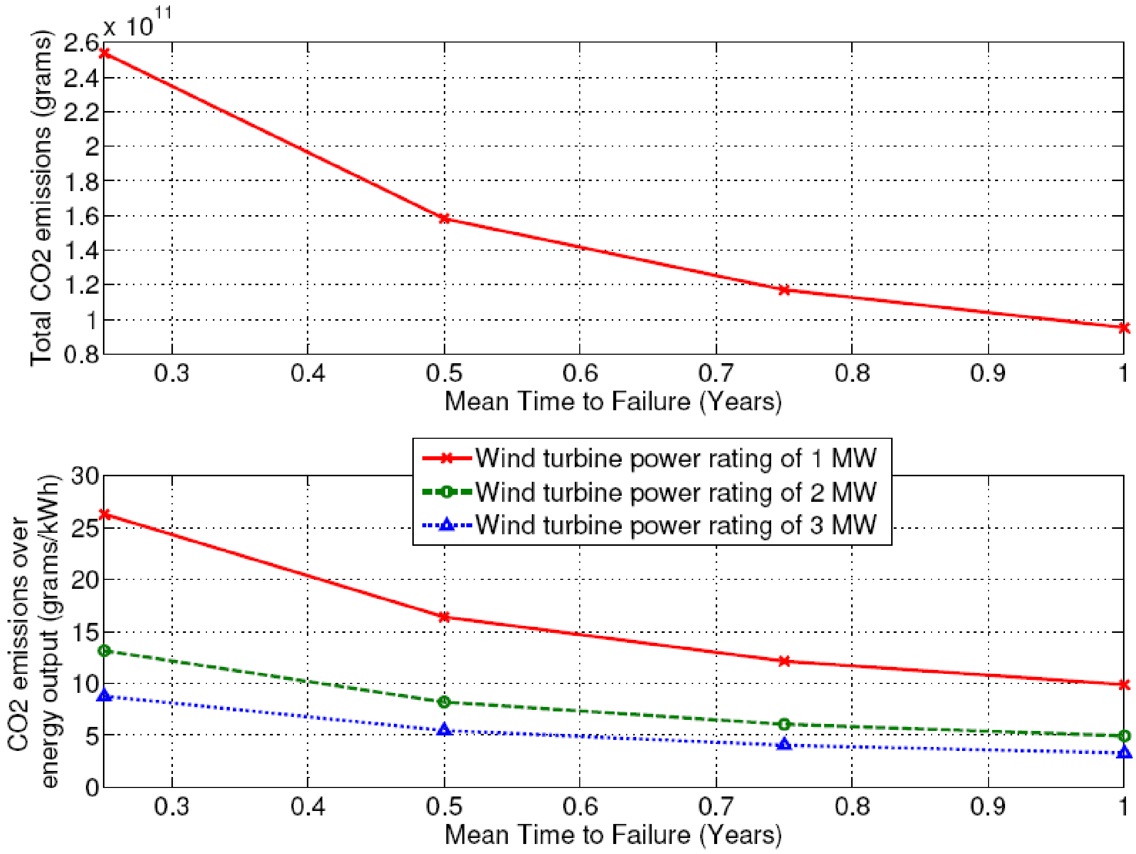

Figure 6.20 The effect of wind turbine power rating on the CO2 emissions and the ratio of CO2 emissions to the energy output. The simulated results are based on the London Array offshore wind farm employing the corrective maintenance strategy.

6.9.5 The effect of the wind farm availability

Figure 6.21 shows the effect of varying the wind farm availability on the total CO2 emissions and the ratio of the CO2 emissions to the energy output, all plotted against wind turbine MTTF. Three different wind farm availability levels have been used for the investigation; 50% (red), 75% (green) and 90% (blue). Considering the total CO2 emissions against the wind turbine MTTF in Figure 6.21, it can be observed that the total CO2 emissions are not affected by the change in the wind farm availability since there is no relationship between the two parameters. Now consider the ratio of CO2 emissions to the energy output against the wind turbine MTTF, it can be observed that the ratio of CO2 emissions to the energy output increases with decreasing wind farm availability level, this being explained by the fact that the energy output decreases as the wind farm availability decreases, as would be expected from equation 4.9 previously presented for the energy model in Chapter 4 (p. 110).

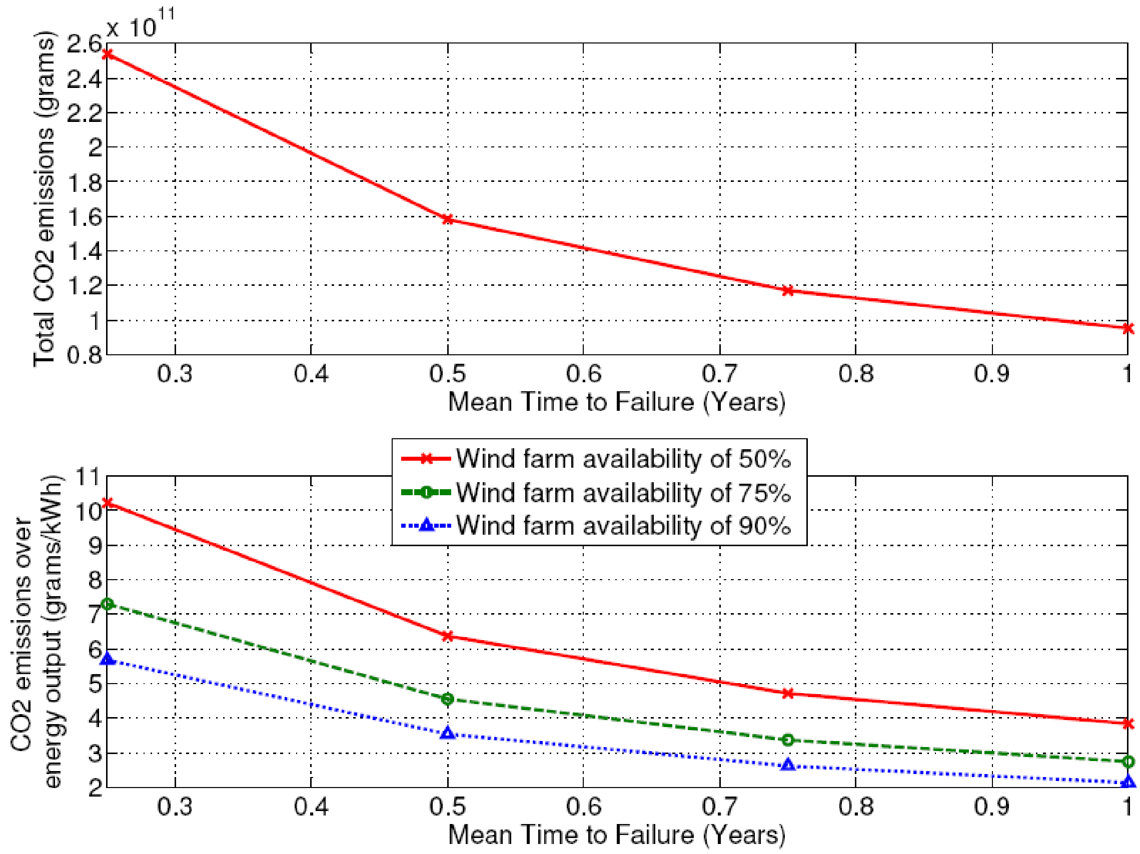

Figure 6.21 The effect of wind farm availability on the CO2 emissions and the ratio of CO2 emissions to the energy output. The simulated results are based on the London Array offshore wind farm employing the corrective maintenance strategy.

6.9.6 The effect of the vessel CO2 emissions

Figure 6.22 shows the effect of varying the vessel CO2 emissions per kilometre travelled on the total CO2 emissions and the ratio of the CO2 emissions to the energy output, all plotted against wind turbine MTTF. Three different values for the CO2 emissions per kilometre travelled by the maintenance vessels have been used for the investigation; 50,000 grams/km (red), 120,000 grams/km (green) and 200,000 grams/km (blue). Considering the total CO2 emissions against the wind turbine MTTF in Figure 6.22, it can be observed that the total CO2 emissions increase as the value of CO2 emissions per km travelled increases, as would be expected from the equations for the CO2 emission calculations presented in Appendix I.

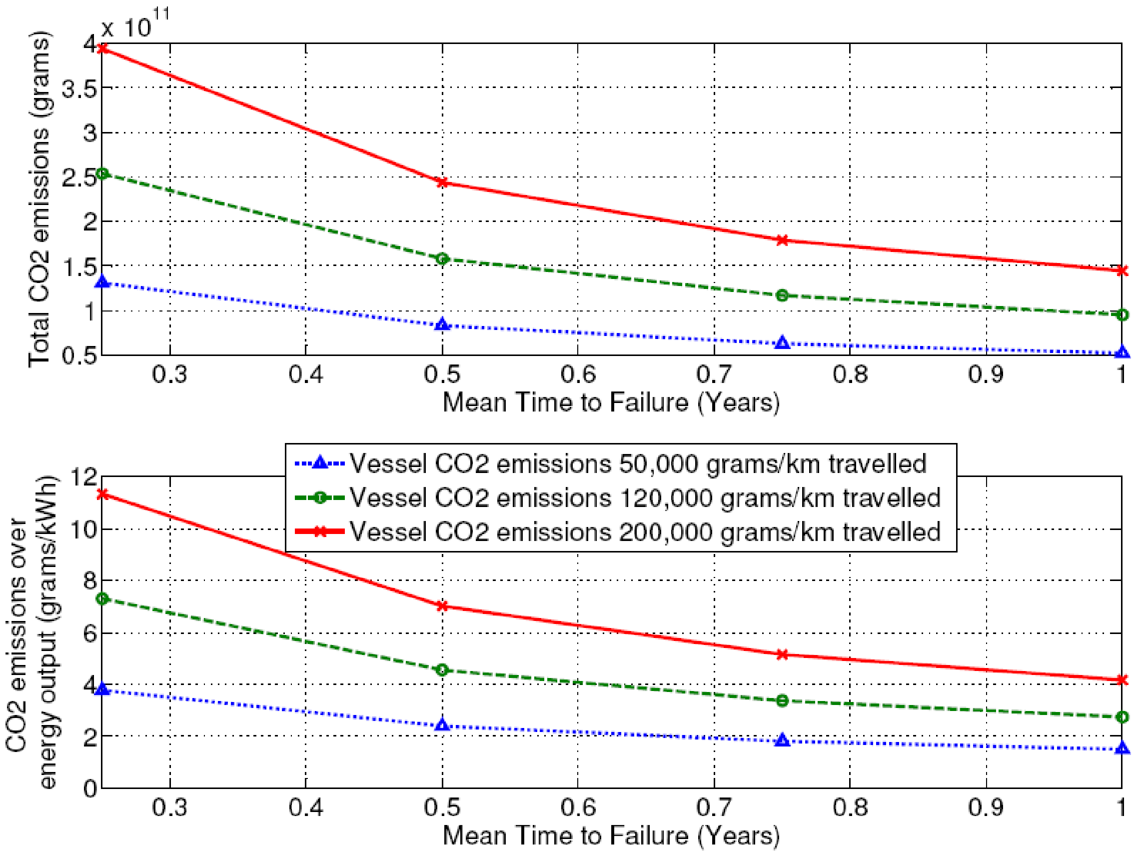

Figure 6.22 The effect of CO2 emissions per kilometre travelled by the maintenance vessels on the CO2 emissions and the ratio of CO2 emissions to the energy output. The simulated results are based on the London Array offshore wind farm employing the corrective maintenance strategy.

Now consider the ratio of CO_2 emissions to the energy output against the wind turbine MTTF, it can be observed that the ratio of CO_2 emissions to the energy output increases as the value of CO_2 emissions per kilometre travelled increases, this being explained by the fact that the energy output is not affected by the change in CO_2 emissions per kilometre travelled as there is no relationship between the two parameters.

6.10 Offshore wind farm case studies investigation for CO2 emissions

Three offshore wind farm case studies, i.e. London Array, Kentish Flats and Opti-Owecs offshore wind farms, have been investigated in order to compare the reactive response and planned intervention maintenance strategies in terms of CO_2 emissions. The London Array offshore wind farm represents a near future project consisted of a large number of wind turbines. The Kentish Flats offshore wind farm is an existing project consisted of a low number of wind turbines located very close to shore. The Opti-Owecs offshore wind farm is a future project located very far from shore.

6.10.1 Case Study 1 – London Array offshore wind farm

The London Array offshore wind farm is a large offshore wind farm located far from shore. Table 6.10 shows the input parameters of the London Array offshore wind farm, which were used for the planned intervention maintenance policy scenarios, i.e. ‘PM 1’ and ‘PM 2’, and the corrective maintenance strategy models to determine the total CO_2 emissions due to maintenance expeditions.

Table 6.10 The parameters of the baseline London Array offshore wind farm.[92]

Parameters	**Value**
Turbine Power rating	3.6 MW
Number of Turbines	175
Distance to shore	46 km
Economic lifetime of project	20 years
Capacity factor	45 %
Wind farm availability	75-80%
Vessel CO2 emissions per km travelled	120,000 grams
Helicopter CO2 emissions per km travelled	31,200 grams
Preventive maintenance period for the corrective maintenance strategy	Once a year

Figure 6.23 shows the comparison between the corrective maintenance strategy model (red) and the planned intervention maintenance policy scenarios ‘PM 1’ (blue) and ‘PM 2’ (green) in terms of the total CO2 emissions due to maintenance expeditions and the ratio of the CO2 emissions to the cumulative energy output, all plotted against wind turbine MTTF. Considering the total CO2 emissions against wind turbine MTTF, the curves that represent the ‘PM 1’ and ‘PM 2’ scenarios are significantly lower as compared to the reactive response curve, this being explained by the lower number of helicopters and vessels journeys for the ‘PM 1’ and ‘PM 2’ scenarios. The curves for the ‘PM 1’ and ‘PM 2’ scenarios appear to be straight lines due to the significant difference with the curve of the corrective maintenance strategy, however the graph on the right hand side of Figure 6.23 shows that the curves are hyperbolic in nature, as expected and as previously explained for Figure 5.17 in Chapter 5 (p. 178).

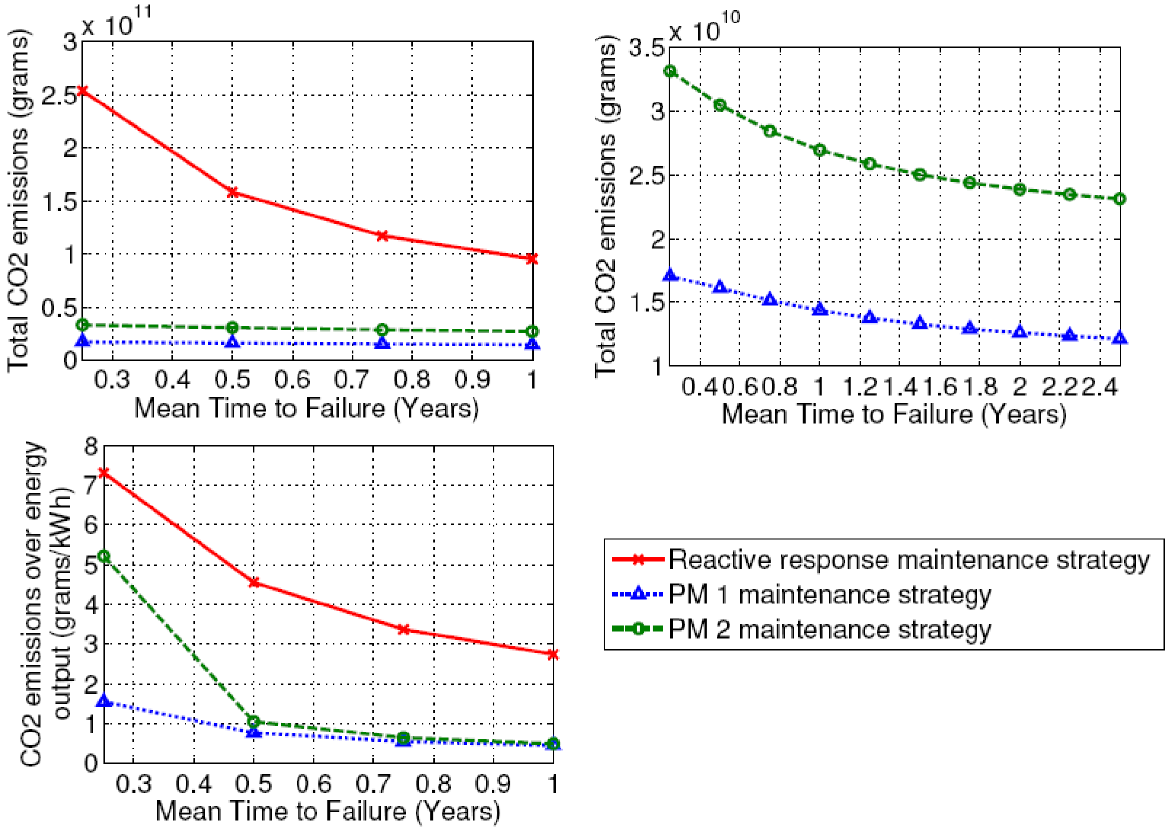

Figure 6.23 The comparison between the planned intervention maintenance policy scenarios, PM1 and PM2, and the corrective maintenance strategy for the London Array offshore wind farm, in terms of total CO2 emissions and the ratio of the CO2 emissions to the energy output.

Now consider the ratio of CO2 emissions to the energy output against the wind turbine MTTF in Figure 6.23. Despite the significant difference in CO2 emissions between the maintenance strategies, the corrective maintenance strategy yields higher energy output, as compared to the 'PM 1' and 'PM 2' scenarios, as would be expected, this being explained by the higher wind farm availability achieved from the corrective maintenance strategy as previously explained in the validation paragraph of planned intervention maintenance policy model in Chapter 5. The curves of the ratio of CO2 emissions to the energy output show comparable results between the different maintenance strategies investigated. For wind turbine MTTF of $0.25 \leq MTTF \leq 0.5$ the 'PM 1' scenario yields 0.8 – 1.7 grams of CO2 per kWh produced, which is significantly lower as compared to the other maintenance strategies. For wind turbine MTTF of $0.5 \leq MTTF \leq 1$ the 'PM 1' and 'PM 2' scenarios yield similar results and as compared to the corrective maintenance strategy they are both found to be 70% on average lower.

6.10.2 Case study 2 – Kentish Flats offshore wind farm

The Kentish Flats offshore wind farm is located in the UK at the Thames Estuary which is online since 2005 feeding the national grid. Table 6.11 gives the input parameters of the Kentish Flats offshore wind farm, which were used for the planned intervention maintenance policy scenarios, i.e. ‘PM 1’ and ‘PM 2’, and the corrective maintenance strategy model to determine the total CO2 emissions due to maintenance expeditions.

Table 6.11 Kentish Flats offshore wind farm parameters.[94,95]

Parameters	Value
Turbine Power rating	3 MW
Number of Turbines	30
Distance to shore	10 km
Economic lifetime of project	20 years
Capacity factor	35 %
Wind farm availability	75-80%
Vessel CO2 emissions per km travelled	120,000 grams
Helicopter CO2 emissions per km travelled	31,200 grams
Preventive maintenance period for the corrective maintenance strategy	Once a year

Figure 6.24 shows the comparison between the corrective maintenance strategy model (red) and the planned intervention maintenance policy scenarios ‘PM 1’ (blue) and ‘PM 2’ (green) for the Kentish Flats offshore wind farm, in terms of the total CO2 emissions due to maintenance expeditions and the ratio of the CO2 emissions to the energy output, all plotted against wind turbine MTTF. Considering the total CO2 emissions against wind turbine MTTF, the curves that represent the ‘PM 1’ and ‘PM 2’

scenarios are significantly lower as compared to the reactive response curve, this being explained by the lower number of helicopters and vessels journeys for the ‘PM 1’ and ‘PM 2’ scenarios. The curves for the ‘PM 1’ and ‘PM 2’ scenarios appear again to be straight lines due to the significant difference with the corrective maintenance strategy, but the graph on the right hand side of Figure 6.24 shows that the curves are hyperbolic in nature, as previously explained for Figure 5.17 in Chapter 5 (p. 178).

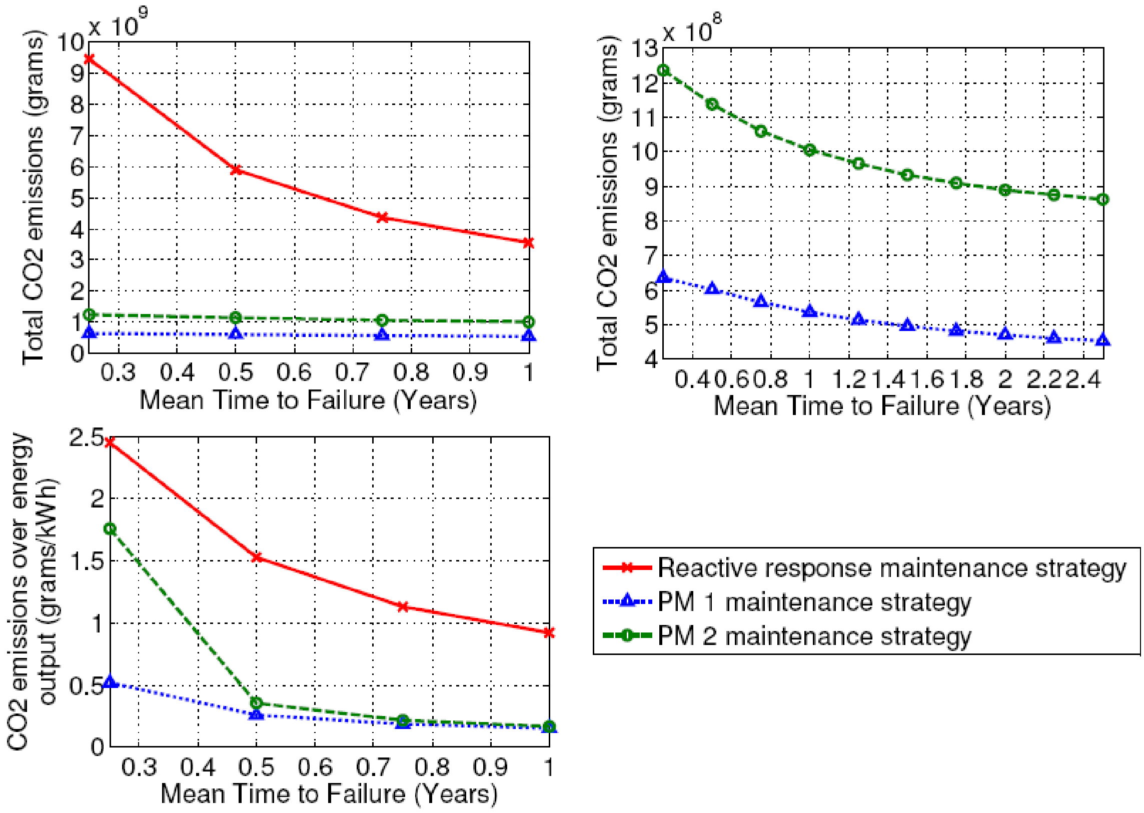

Figure 6.24 The comparison between the planned intervention maintenance policy scenarios, PM1 and PM2, and the corrective maintenance strategy for the Kentish Flats offshore wind farm, in terms of total CO2 emissions and the ratio of the CO2 emissions to the energy output.

Now consider the ratio of CO2 emissions to the energy output against the wind turbine MTTF in Figure 6.24. For wind turbine MTTF of 0.25≤MTTF≤0.5 the ‘PM 1’ scenario yields 0.25 – 0.5 grams of CO2 per kWh produced, which is significantly lower as compared to the other maintenance strategies. For wind turbine MTTF of

0.5≤MTTF≤1 the 'PM 1' and 'PM 2' scenarios yield similar results and as compared to the corrective maintenance strategy they are found to be 60% on average lower.

6.10.3 Case Study 3 – Opti-Owecs offshore wind farm

The Opti-OWECS (Optimisation of Offshore Wind Energy Converters) project used state-of-the-art offshore wind turbine technology to investigate practical solutions for O&M practices for a large offshore wind farm, with the primary aim of reducing the electricity cost.[72,73] The distance to shore of the Opti-Owecs offshore wind farm has been set at 100 km to represent a possible future location for offshore wind farms. The failure rates of the offshore wind turbines used in the Opti-Owecs project were between 1.43 and 1.79 per year (or 0.558≤MTTF≤0.698). Table 6.12 gives the input parameters of the Opti-Owecs offshore wind farm, which were used for the planned intervention maintenance policy scenarios, i.e. 'PM 1' and 'PM 2', and the corrective maintenance strategy model to determine the total CO2 emissions due to maintenance expeditions.

Table 6.12 Opti-Owecs offshore wind farm parameters.[72,73]

Parameters	Value
Turbine Power rating	3 MW
Number of Turbines	100
Distance to shore	100 km
Economic lifetime of project	20 years
Capacity factor	34 %
Wind farm availability	75%
Vessel CO2 emissions per km travelled	120,000 grams
Helicopter CO2 emissions per km travelled	31,200 grams
Preventive maintenance period for the corrective maintenance strategy	Once a year

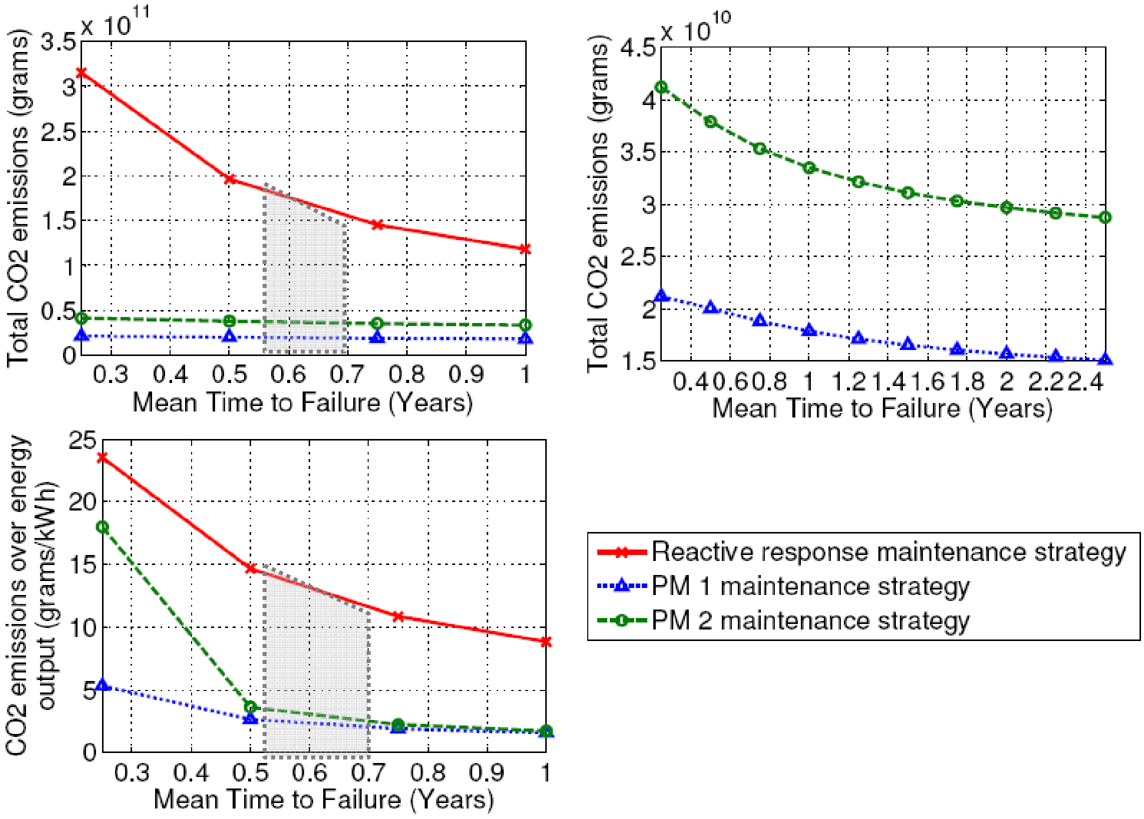

Figure 6.25 The comparison between the planned intervention maintenance policy scenarios, PM1 and PM2, and the corrective maintenance strategy for the Opti-Owecs offshore wind farm, in terms of total CO2 emissions and the ratio of the CO2 emissions to the energy output.

Figure 6.25 shows the comparison between the corrective maintenance strategy model (red) and the planned intervention maintenance policy scenarios ‘PM 1’ (blue) and ‘PM 2’ (green) for the Opti-Owecs offshore wind farm, in terms of the total CO2 emissions due to maintenance expeditions and the ratio of the CO2 emissions to the energy output, all plotted against wind turbine MTTF. Since the failure rates of the offshore wind turbines used in the Opti-Owecs project are between 1.43 and 1.79 per year (or $0.558 \leq MTTF \leq 0.698$), the simulated results that reflect this range are shown in the shaded area on all the graphs in Figure 6.25. Considering the total CO2 emissions against wind turbine MTTF, the curves that represent the ‘PM 1’ and ‘PM 2’ scenarios are significantly lower as compared to the reactive response curve, this being explained by the lower number of helicopters and vessels journeys for the ‘PM 1’ and ‘PM 2’ scenarios. The curves for the ‘PM 1’ and ‘PM 2’ scenarios appear again to be straight lines due to the significant difference with the corrective maintenance strategy, but the graph on the right hand side of Figure 6.28 shows that the curves are hyperbolic in nature, as would be expected and as previously explained for Figure 5.17 in Chapter 5.

Now consider the ratio of CO2 emissions to the energy output against the wind turbine MTTF in Figure 6.25. Despite the significant difference in CO2 emissions between the maintenance strategies, the corrective maintenance strategy yields higher energy output, as compared to 'PM 1' and 'PM 2' scenarios, which in turn results in the curves of the ratio of CO2 emissions to the energy output to give comparable results between the maintenance strategies. For wind turbine MTTF of $0.55 \leq MTTF \leq 0.69$ the 'PM 1' and the 'PM 2' scenarios yield similar results between 3 – 4 grams of CO2 per kWh produced, but the corrective maintenance strategy yields significantly higher results between 12 – 15 grams of CO2 per kWh produced. For lower wind turbine MTTF the difference in the ratio of CO2 emissions per kWh produced between the planned intervention maintenance policy scenarios and the corrective maintenance strategy becomes even higher, where the corrective maintenance strategy yields up to 25 grams of CO2 per kWh produced.

6.10.4 Bio-diesel analysis

This paragraph presents the effect of using bio-fuels on CO2 emissions as a substitute to the conventional diesel for the maintenance transportation means for offshore wind farms. Bio-fuels for transport, including ethanol, bio-diesel, and several other liquid and gaseous fuels, have the potential to displace a substantial amount of petroleum around the world over the next years.[102,104] Bio-diesel can be used (alone, or blended with conventional petro-diesel) in diesel engines and it is being produced or used commercially in numerous countries around the world.[102,104] The following points summarise the benefits of using biofuels:[102,103,104,105]

- **Commercialisation.** Bio-fuels may be easier to commercialise than other alternative fuels, considering performance and infrastructure. Bio-fuels have the potential to leapfrog, i.e. a theory in which developing countries may accelerate development by skipping inferior, less efficient technologies.

- **CO2 emissions reduction.** Bio-fuels can play a significant role in climate change policy and in measures to reduce greenhouse gas emissions. Bio-fuels have become particularly intriguing because of their potential to greatly reduce CO_2 emissions throughout their fuel cycle, as shown in the Figures in Appendix I. Bio-diesel is the first and only alternative fuel to have a complete evaluation of emission results and potential health effects submitted to the U.S. Environmental Protection Agency (EPA) under the Clean Air Act Section 211(b), as shown in the Figures in Appendix I. The average CO2 reduction achieved by the B20 bio-diesel blend is 15% and for the B100 bio-diesel blend is 45%, as compared to conventional diesel fuels, as shown in the Figures in Appendix I. B20 bio-diesel fuel refers to a product with a 20% blend of bio-diesel to conventional diesel fuel, and similarly B100 refers to a product of 100% of bio-diesel.

- **Conventional fuel dependency.** Bio-fuels can readily displace petroleum fuels and, in many countries, can provide a domestic rather than imported source of transport fuel. Even if imported, bio-diesel will likely come from regions other than those producing petroleum (e.g. Latin America rather than the Middle East), creating a much broader global diversification of supply sources of energy for transport.

On the other hand there are some disadvantages related to the production and use of bio-diesel for transportation:

- **Efficiency**. Conventional diesel engines convert the energy from bio-diesel fuels into useful work with reduced efficiency, as shown in the Figures in Appendix I, between 20 to 29%.

- **Cost of production**. The cost of bio-diesel is at present time higher than conventional fuel for use in transportation, as shown in the Figures in Appendix I. This is due to the fact that the production methods are still immature as compared to the conventional fuel plants.

- **Harvesting**. There has been a large debate over the use of crop growing and harvesting for the purpose of bio-diesel production. This is because these crops could be used instead to supply food to countries that experience high mortality rates due to lack of food.

6.10.5 The effect of using bio-diesel fuels on CO2 emissions

The reduction in green house gases that could be achieved from the use of bio-diesel fuels for the vessels and helicopters used for the maintenance of offshore wind farms is shown in the following figures. B20 and B100 bio-diesel blends have been used for both the planned intervention and corrective maintenance strategies to determine the CO2 emissions reduction.

Figure 6.26 shows the comparison between the CO2 emissions when using bio-diesel fuels as a replacement for the conventional diesel fuels for the transportation means. Considering the corrective maintenance strategy model it can be observed that a significant reduction in the CO2 emissions and consequently in the ratio of CO2 emissions over the energy output could be achieved if the bio-diesel fuels were used. The same observation can be made by considering the CO2 emissions when using the planned intervention maintenance policy model in Figure 6.26.

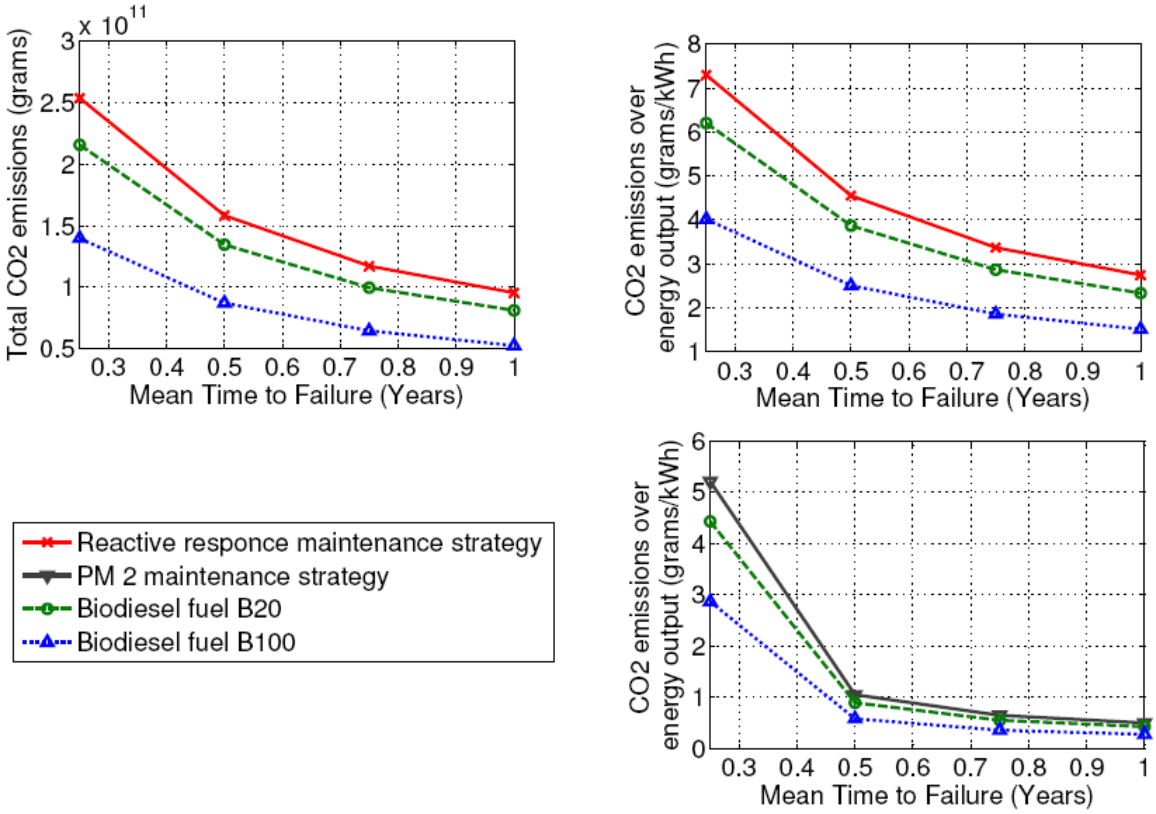

Figure 6.26 The comparison between the CO2 emissions for using biodiesel fuels, i.e. B20 and B100, as a replacement for the conventional diesel fuels for the transportation means for the London Array offshore wind farm

6.10.6 Comparison of simulated results for the CO2 emissions

The results for the CO2 emissions for offshore wind farms for the three case studies; London Array, Kentish Flats and Opti-Owecs offshore wind farms were presented in this Chapter in terms of total CO2 emissions and the ratio of CO2 emissions to the energy output. These results are summarised in Table 6.13, for comparison purposes between the different maintenance strategies investigated, and are divided into two sections for different wind turbine MTTF ranges, i.e. $0.25 \leq MTTF \leq 0.5$ and $0.5 \leq MTTF \leq 1$, that represent the reliability of offshore wind turbines, as explained previously in the reliability model in Chapter 4 (p. 96).

Considering the total CO2 emissions for all the case studies in Table 6.13, then the results show significant variation between the reactive response and planned intervention maintenance policy, which is explained by the fact that the corrective maintenance strategy achieves higher wind farm availability, as compared to ‘PM 1’ and ‘PM 2’ scenarios, by performing a significant high number of maintenance expeditions to the offshore wind farm. Considering the wind turbine MTTF range of $0.25 \leq MTTF \leq 1$, then the ‘PM 1’ scenario yields the smallest amount of CO2 emissions for all the case studies as compared to the ‘PM 2’ scenario and the corrective maintenance strategy. A significant conclusion reached from the comparison of the simulated results between the different case studies in Table 6.13 is that the Opti-Owecs offshore wind farm achieved the highest value of CO2 emissions, which indicates the significant effect of the distance to shore. It is interesting to observe that for both wind turbine MTTF ranges, the planned intervention maintenance policy achieves a reduction of an average of 70% in the CO2 emissions, as compared to the corrective maintenance strategy.

Now consider the ratio of CO2 emissions to the energy output for all the case studies in Table 6.13. The results show a significant difference between the reactive response and planned intervention maintenance policy, which is explained by the fact that despite the corrective maintenance strategy achieves higher energy output, as compared to the ‘PM 1’ and ‘PM 2’ scenarios, the significantly higher number of maintenance expeditions result in higher CO2 emissions per kWh produced. The Opti-Owecs offshore wind farm achieved the highest ratio of CO2 emissions to the energy output, which also indicates the significant effect of the distance to shore. An important conclusion reached from the comparison of the results in Table 6.13 is that for both wind turbine MTTF ranges, the planned intervention maintenance policy achieves a reduction of an average of 80% in the ratio of CO2 emissions to the energy output, as compared to the corrective maintenance strategy.

Table 6.13 Results for the calculation of CO2 emissions for the reactive response (RR) and planned intervention maintenance stratety (PM 1 and PM 2) for all the case studies investigated in this chapter.

Case study		**Total CO2 emissions (grams * 10^{10})**		**CO2 emissions per kWh (grams/kWh)**	
Reliability level		0.25≤MTTF≤0.5	0.5≤MTTF≤1	0.25≤MTTF≤0.5	0.5≤MTTF≤1
London Array	**RR**	15.8-25.3	9.5-15.8	4.6-7.3	2.7-4.6
	PM 1	1.6-1.7	1.4-1.6	0.76-1.6	0.45-0.76
	PM 2	3-3.3	2.7-3.3	1-5.2	0.5-1
Kentish Flats	**RR**	0.589-0.945	0.355-0.589	1.5-2.5	0.91-1.5
	PM 1	0.06-0.064	0.05-0.06	0.26-0.51	0.15-0.26
	PM 2	0.11-0.12	0.1-0.11	0.35-1.7	0.16-0.35
Opti-Owecs	**RR**	19.7-31.5	11.8-19.7	14.66-25	8.8-14.66
	PM 1	2-2.11	1.7-2	2.6-5.3	1.56-2.6
	PM 2	3.78-4.12	3.34-3.78	3.61-17.9	1.71-3.61
Biodiesel	**B20**	13.5-21.6	8.1-13.5	3.9-6.2	2.3-3.9
	B100	8.7-14	5.2-8.7	2.5-4	1.5-2.5

The use of bio-diesel as a fuel for the vessels and helicopters employed for the maintenance of offshore wind farms, has shown a significant reduction in the CO2 emissions. This observation indicates that when planning for a renewable energy project to mitigate the CO2 emissions, the use of bio-fuels for the maintenance expeditions should be highly considered.

6.10.7 Comparison of the simulated results against published data

The results presented in Table 6.13 for the ratio of the CO2 emissions to the energy output can be used to compare the offshore wind farms against other power plants. Table 6.14 gives the CO2 emissions per kWh produced by different conventional power plants and also solar and hydro power projects, where the range in the reported values indicates varying location, efficiencies and availability factors. Considering the CO2 emissions for the manufacturing, transportation and installation of the offshore wind farms, they result in an average of 16.5 grams of CO2 per kWh produced, as previously explained in Chapter 2. When adding this value to the ratio of CO2 emissions to energy output associated with the maintenance of the offshore wind turbines, as presented in Table 6.13, then for the future offshore wind farms, e.g. Opti-Owecs project, the total ratio of CO2 emissions to the energy output could reach up to 41.5 grams of CO2 per kWh produced by employing the corrective maintenance strategy, whilst when employing the planned intervention maintenance policy only 21.8 grams of CO2 per kWh are produced.

Table 6.14 CO2 emissions per kWh produced by power plants.[102,104,105,107]

Power plant	Ratio of CO2 emissions to the energy output (grams/kWh)
Coal	815 – 990
Gas	356 – 653
Solar	50 – 95
Nuclear	6 – 26
Hydro	3 – 18

When comparing these results to the results presented in Table 6.14 it can be concluded that the total CO2 emissions per kWh produced from offshore wind farms are not negligible and are found to be significantly higher as compared to the nuclear and hydro power plants, when considering the employment of the corrective maintenance strategy, whilst by employing the planned intervention maintenance policy for future offshore wind farms, it could possibly result in a significant reduction of the CO2 emissions per kWh produced, while the results are found to be directly comparable with the hydro power plants.

6.11 Conclusions

This chapter presented the investigations on the viability of the planned intervention maintenance policy for offshore wind farms as compared against the current maintenance practices. Different offshore wind farm case studies investigations were carried out to determine the benefits and drawbacks of the planned intervention maintenance policy with variations in the key input parameters of the offshore wind farm over a range of input variables. The comparison between results obtained from the planned intervention maintenance policy scenarios have resulted in significant conclusions on the application of the proposed solution for the maintenance practices for offshore wind farms.

The significant conclusions reached from the comparison of the results between the planned intervention maintenance policy and the corrective maintenance strategy are that the proposed solution may not be an economic option, when considering small offshore wind farms located close to shore consisted of small number of wind turbines at low power rating. However, when considering future offshore wind farms with high number of wind turbines located far offshore with higher power rating, then the planned intervention maintenance policy could potentially produce results that are significantly better as compared to the corrective maintenance strategy, in terms of project’s economic viability, i.e. LPC of energy.

When considering the results obtained for the percentage of maintenance cost in the CAPEX versus wind turbine MTTF, they have been used for comparing the planned intervention maintenance policy between the different case studies investigated in order to identify the key parameters that affect the economics of the projects. When comparing the percentage of maintenance cost in the CAPEX with the results obtained from the London Array offshore wind farm, it can be concluded that the percentage of maintenance cost in the CAPEX for the Kentish Flats offshore wind farm is found to be significantly higher, which can be explained by the fact that the cost of each installed wind turbine, i.e. CAPEX divided by the total number of wind turbines in the wind farm, for the London Array is calculated to be 11.2 million pounds per wind turbine and for the Kentish Flats is calculated to be 3.5 million pounds per wind turbine. This indicates that the CAPEX of the Kentish Flats offshore wind farm is significantly lower, as compared to the London Array.

Considering the comparison of the LPC of energy between the London Array and the Kentish Flats offshore wind farms, where the results indicate that the Kentish Flats achieves lower LPC of energy, this being a direct result of the difference in the CAPEX of each project. The Kentish Flats is an offshore wind farm located closer to shore (25 km) and at shallower waters, which decreases the cost of wind turbine foundations, cables, and installation process, which account for around 40% of the CAPEX,[72,73] as compared to the London Array offshore wind farm. This conclusion could also be reached by dividing the CAPEX of each case study with the total number of wind turbines in the wind farm to calculate the cost per installed wind turbine. For the Beatrice offshore wind farm it is calculated to be 17.5 million pounds per wind turbine installed, for the London Array offshore wind farm is calculated to be 11.2 million pounds and for the Kentish Flats is 3.5 million pounds per wind turbine installed. These results point out the significant effect of the distance to shore and the water depth on the LPC of energy of offshore wind farms.

The comparison of the results from the Kentish Flats case study against the results obtained from the DOWEC project indicate that the DOWEC project yields significantly lower LPC of energy, despite the fact that it has a considerably higher calculated cost per installed wind turbine, i.e. 5.84 million pounds. This could be explained by the fact that the DOWEC project achieves significantly higher energy output, as compared to the Kentish Flats, since each wind turbine has twice the power rating of those installed in the Kentish Flats. The significant conclusion reached from the observation of these results is that the wind turbine power rating has a higher effect on the LPC of energy than the distance to shore and the water depth.

The comparison between the planned intervention maintenance policy and the corrective maintenance strategy in terms of CO2 emissions has been investigated in this Chapter. The significant conclusions reached from the comparison of the results is that the planned intervention maintenance policy offers much lower CO2 emissions for all the offshore wind farm case studies investigated across the range of wind turbine reliability levels. A further significant conclusions reached is that the CO2 emissions from offshore wind farms for the construction, installation, decommissioning and maintenance activities are not negligible as has been falsely believed and show a significant magnitude as compared to the other renewable energy sources.

Considering the CO2 emissions for the manufacturing, transportation and installation of the offshore wind farms, they result in an average of 16.5 grams of CO2 per kWh produced, as previously detailed in Chapter 2. When adding this value to the ratio of CO2 emissions to energy output associated with the maintenance of the offshore wind turbines, that has been calculated in this chapter, then for future offshore wind farms the total ratio of CO2 emissions to the energy output could reach up to 41.5 grams of CO2 per kWh produced by employing the corrective maintenance strategy, whilst when employing the planned intervention maintenance policy only 21.8 grams of CO2 per kWh are produced. These results show the significant reduction in CO2 emissions achieved by substituting the current maintenance practices with the proposed solution of planned internvetion.

7 Wind Turbine System Redundancy

7.1 Introduction

This chapter explains the development of a redundancy model for offshore wind turbine systems and uses it to assess the technical challenge of the low reliability components of offshore wind farms. It has already been shown in the reliability model in Chapter 4 that the wind turbine component that suffers the highest failure rate is the electrical system, which accounts for an average of 22% of the total wind turbine failures. The redundancy model that is developed in this Chapter to represent the converter system of the wind turbine and allows investigations to be performed on the effects on the wind farm availability, cumulative energy output, LPC of energy and CO2 emissions on reliability. Three different offshore wind farm case studies have been investigated in the following paragraphs.

7.2 Converter system failures

Considering the wind turbine reliability study, as previously presented in Chapter 4, it was identified that the components of the wind turbine system more prone to failures are the components of the electrical systems, which account for an average of 22% of all the wind turbine failures. Considering the above observation, it becomes apparent that it is important for the future development of the wind turbines and the economical viability of the future offshore wind farms to address the reduced reliability levels of these components.

An attempt to address this technical challenge is performed in this chapter through an optimisation of the reliability of the electrical systems of the wind turbines, by investigating a redundancy model for the converter system. For this redundancy model 3 different case studies of offshore wind farms are used, i.e. the London Array, the Kentish Flats and the DOWEC project, in order to identify how the redundancy model affects the reliability of the wind turbines, the overall availability levels of the wind farm, the cumulative energy output, the LPC of energy and the CO2 emissions.

The electrical system failures of the wind turbine are categorised in the following components, as described in the wind turbine reliability database of WMEP:[79]

- Converter system,
- Fuses,
- Switches,
- Cables connections,
- Other converter related failures.

Figure 7.1 shows a typical percentage breakdown of the electrical system failures of a wind turbine system.

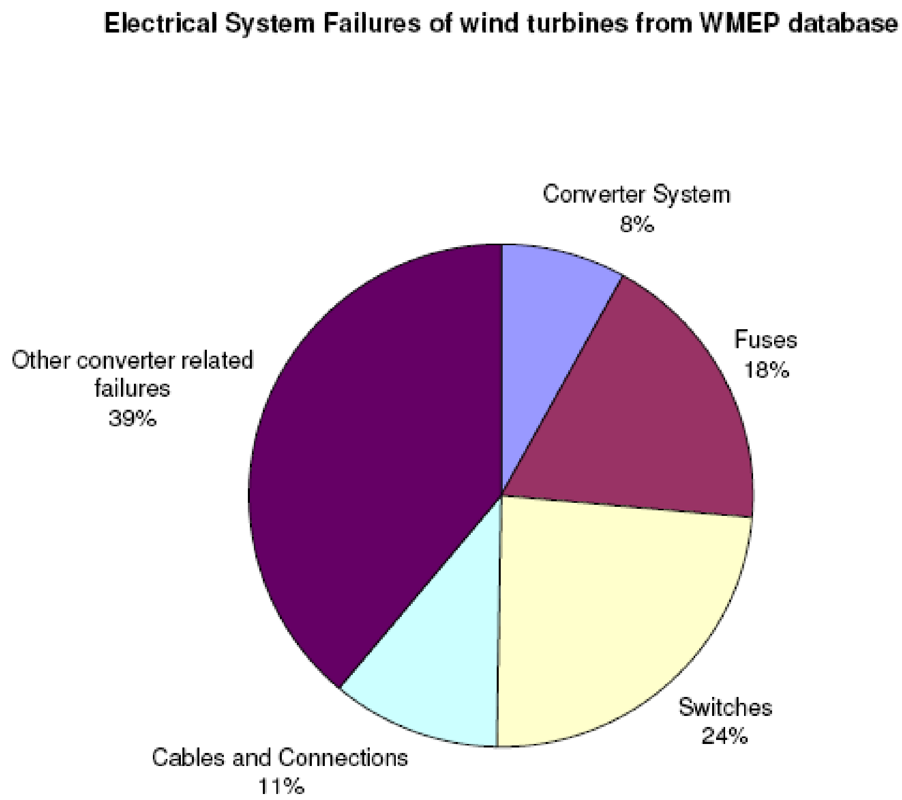

Figure 7.1 Percentage of component failures for the electrical system of wind turbines. [79]

It is reported in a number of studies that the increased failures of the electrical components of the wind turbines are directly related to the operating conditions of the converter system or indirectly related to malfunctions of the converter components, i.e. malfunctions in the IGBT switches and the converter control unit resulting in fuse and cable connections failures.[109,110,111,112,113,114] These studies explain that the load conditions of full output current at very low output current frequencies for the converter system, as happens for the wind turbines, causes thermal fatigue of the IGBT-switches and the converter control unit, which results in a converter failure.[109,110,111,112,113,114] Further details for the wind turbine converter related failures are presented in Appendix J.

7.2.1 Different approaches to system redundancy

Considering the technical challenge of increased failure rate of the converter system, as presented in the previous paragraph, different technical approaches could be established to address it:

- **Modify the existing converter** system design to change the operating conditions in order to minimise the risks of failures,
- **Redesign the converter** system from the beginning in order to operate at the desired levels, aiming to minimise the failure rates and
- **Use the existing converter** system design in a redundancy model to increase the reliability of the wind turbine system.

Using the existing converter design to address the technical challenge of the electrical system in a wind turbine, represents a common approach to model redundancy in a system, which is investigated in this chapter. Considering a redundancy model applied to the wind turbine, then the critical components should have at least one independent backup component to ensure that system functionality continues in the event of a failure. For the system to be designed for redundancy then the overall system operation should not be impacted by the failure of one of the redundant components, and should continue to function at acceptable performance levels after the loss of redundant components.[3] Considering a system with a component that suffers high failure rates in a wind turbine, e.g. electrical system, then Figure 7.2 shows a schematic diagram of a redundancy model applied to that component:

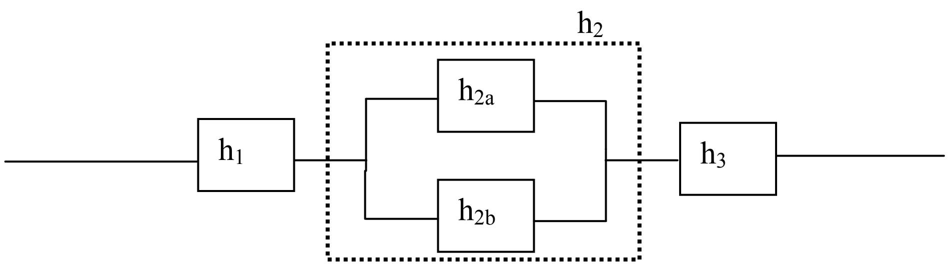

Figure 7.2 A schematic diagram of the redundancy of a component in a system

Considering Figure 7.2, then h_1, h_2 and h_3 represent the failure rates of different components in a system. The redundancy model has been applied to the component with failure rate h_2 where two redundant components have been employed having h_{2a} and h_{2b} failure rates. For the system to fail both redundant components should fail.

7.2.2 Different redundancy techniques

The redundancy of a critical component is achieved with three different techniques, i.e. cold, warm and hot standby redundancy:[3]

- **In a cold standby redundant system**, the redundant (or secondary) component of the system is switched on only when the primary component fails, i.e. initially one component will be operating to serve the full load and should this primary component fail, then the redundant component is switched on to serve the full load. For example, in the event of a power cut in a hospital (the primary component fails) then batteries and generators (redundant component) would switch on instantly to provide electricity.[3] Since it is a dormant equipment, its reliability is a function of its failure rate (λ) and the period between preventive maintenance tasks (T), i.e. its probable unavailability (P) could be calculated by:[162]

$$P = 1 - e^{-0.5\lambda T}$$

  The redundant component in a cold standby system may not work when required and it may be installed for a long time before it is required to operate. It therefore needs to be inspected (preventively maintained) regularly to verify that it works. In addition, the use of equipment, e.g. sensors that detect that the primary component has failed is essential to switch the operation to the redundant component. However, this switching equipment has a reliability level, which could be important and should therefore be taken into consideration.[3,162]

- **In a warm standby redundant system**, the redundant component would be sharing only a partial load along with the primary component, i.e. the failure rate of the redundant component is less than that of the primary component. The primary and the secondary components work simultaneously at different power loads and there is always the risk of total system failure should both components fail. Considering a warm standby redundant system then the impact of a failure of either the primary or secondary component on the (power) output depends and varies with the percentage of the power load that each component is using. It should also be considered here that there might be the possibility that should the primary component fail then the whole system might fail, as the redundant component might not be capable of keeping the system operating on its own.

- **In a hot standby redundant system**, there is no primary and secondary components as happens for the two previous redundancy techniques, i.e. the cold and warm standby redundant systems, however the components for a hot standby redundancy share equal load and work simultaneously, which indicates that they will have the same failure rate, therefore a hot standby redundancy model can be treated as a parallel configuration system. Considering a parallel configuration, the system only fails when all the redundant components fail, whilst when one of the redundant components fail the system should continue to operate only with a degradation of the maximum output load. Parallel redundant components are introduced when the reliability requirements for a system are very high, e.g. the use of more than one engines in aircrafts is a parallel configuration. However, it is reported that in most cases the hot standby redundant systems will increase the cost, complexity, size and/or weight of the system, as compared against the conventional system configuration without any redundancy, while it is also suggested that the number of redundant components should be carefully determined to avoid over-design disadvantages, e.g. a cost increase.[3]

Table 7.1 below gives the relationship of the failure rates between the primary and secondary components of a redundant system for the three different redundancy techniques previously explained. If $h_p(t)$ and $h_s(t)$ represent the failure rate functions of the primary and secondary component respectively then their relationship is given in the following Table:

Table 7.1 The types of standby redundancy models and the corresponding failure rates between primary (h_p) and secondary (h_s) components.[3]

Redundancy Technique	**Relationship of the failure rate functions**
Cold Standby	$h_s(t) = 0$
Warm Standby	$h_p(t) > h_s(t)$
Hot Standby	$h_p(t) = h_s(t)$

7.2.3 Redundancy of the wind turbine converter system

Considering a redundancy model on the wind turbine converter system then the three techniques explained in the previous paragraph could each be applied and would result in different technical and economical solutions. However, one of the major manufacturers (Gamesa Eolica)[109,110,111,112] of wind turbines has identified the technical challenge of the reduced reliability of the converter system and has suggested a prototype design of a wind turbine for the offshore environment that employs a hot standby redundancy model with 6 redundant converter systems working in parallel, as shown in Figure 7.3, where the converter system consists of 6 identical converter modules.[109,110,111,112] This system configuration will be examined in this chapter to quantify the possible technical and economical benefits over the conventional system configuration with one converter system for the wind turbine.

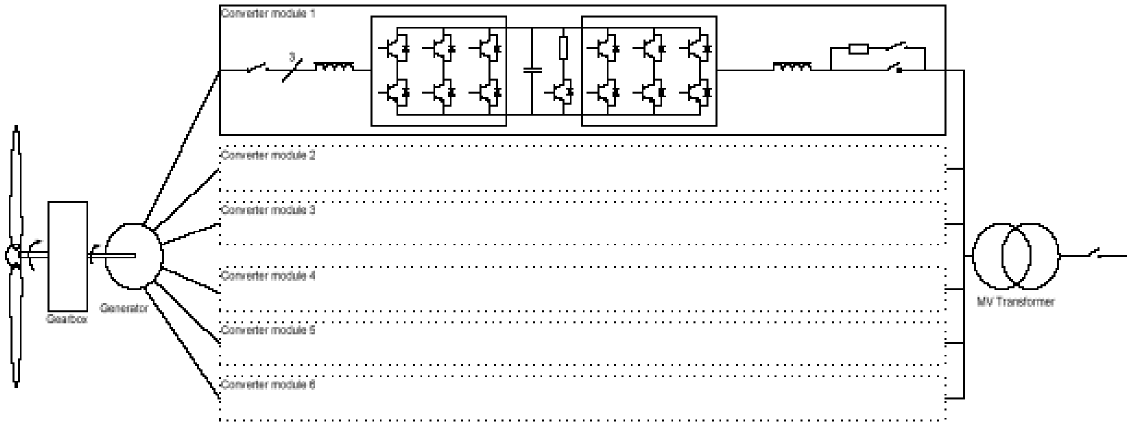

Figure 7.3 Diagram of the multi-converter system of the Gamesa G10x 4.5 MW wind turbine.[109,110,111,112]

Considering the wind turbine redundant system presented in Figure 7.3, the parallel converter modules are connected to a medium-speed, multi-pole, permanent-magnet generator with 6 separate winding systems which are electrically and magnetically independent.[109,110,111,112] The advantage of such a system design is that should one of the converter modules fails, the wind turbine would still be capable of supplying 5/6 of the rated output power to the grid, as claimed by the manufacturer, i.e. the loss of energy in case of one converter failure is significantly lower as compared to the conventional wind turbine system. The wind turbine system configuration explained above fulfils the criteria of a hot standby redundancy model, i.e. the parallel working converters are independent of each other, while when a failure in one of the converters is identified, the operating state of the other redundant converters is not affected, while the wind turbine continues to function at acceptable performance levels, only with reduced power output.

However, it should be mentioned at this point that when this redundancy model is applied on a multi-phase generator then should one of the converter systems fail, then the system might become (electrically) unbalanced and certain actions would be required to deal with this unbalance, e.g. if one of the current phases fails in one of the parallel converters then the other two phases serving the failed converter should be switched off to prevent electrical generator torque imbalance.[115] A further point that should be mentioned is that in a multiple parallel converter system it is reported that a 5% increase on the initial cost of the multi-phase generator and transformer should be considered, as compared to a conventional three-phase generator wind turbine system.[116,117] In addition, a further issue that arises from the application of the hot standby redundancy on offshore wind turbines is the available space in the nacelle for the accommodation of extra redundant converters, despite the downgrade in converter power load resulting in its downgrade in size,[118] which could potentially increase the cost of the nacelle.

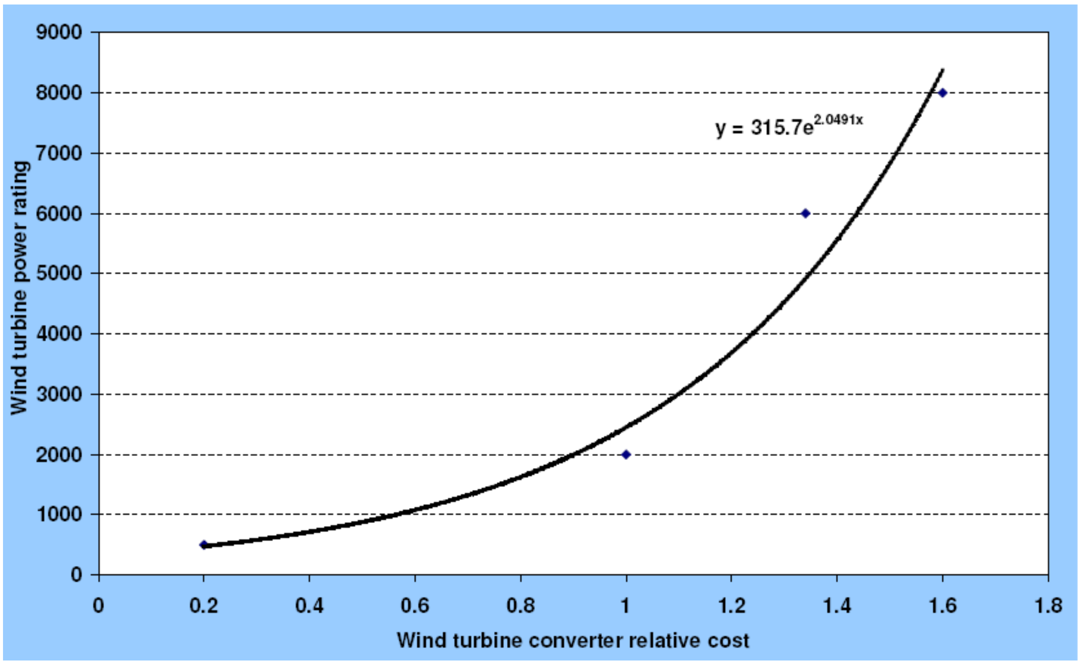

Figure 7.4 The relative cost of wind turbine converter against wind turbine power rating.[118] The data in this graph are based on the consideration that one converter exists per wind turbine that works on full load at the wind turbine's maximum power rating.

When considering the multi-parallel converter system of the wind turbine as presented in Figure 7.3 then 6 redundant converters have substituted the conventional converter system with one converter serving the full power load of the 4.5 MW wind turbine. These 6 redundant converters have been downgraded considering their output power load and each of them covers 750 kW of the wind turbines' total power load.[109,110,111,112] The cost of each of the redundant converters is expected to be reduced according to their output power load, as compared to the conventional wind turbine converter system, this being explained in Figure 7.4 which gives the relationship between the relative cost of the wind turbine converter and the output power load of the wind turbine.[118] It can be observed in Figure 7.4 that the relationship between the converter cost and its power load is not linear.

It should be expected that the number of redundant converters needed is dependent upon the maintenance strategy employed and the outputs of the wind farm, in terms of wind farm availability, energy output, LPC of energy and CO2 emissions. These wind farm outputs are each affected differently by the hot standby redundancy model and this chapter has set out an investigation to analyse how each output parameter is affected. The aim of this investigation is to identify whether the proposed wind turbine system design using 6 redundant converters could yield better outputs, as compared to the conventional wind turbine system. Furthermore, investigations have considered whether a smaller number of redundant converters could yield better output results by considering the costs associated with added converters and the costs for their maintenance for different offshore wind farm case studies.

7.3 The development of the hot standby redundancy model

The reliability function of a hot standby redundant system can be calculated using the equations for parallel system configurations, as explained earlier in this chapter (p. 275):[3,162]

$$R_s(t) = 1 - \prod_{1}^{n} \left[1 - R_i(t)\right] \tag{7.1}$$

Where,

R_s	is the system reliability using a redundancy model, i.e. the converter system, as a function of time t.
n	is the number of redundant components in the system.
R_i	is the reliability of one of the redundant components.

If $h_i(t)$ represents the failure rate function of one of the redundant component, then the reliability function of a parallel configuration in equation 7.1 can be rewritten as:[3]

$$R_s(t) = 1 - \prod_{i=1}^{n}\left[1 - \exp\left(-\int_0^t h_i(t)dt\right)\right] \tag{7.2}$$

If $h_{system}(t)$ represents the failure rate function of the parallel configuration system then it can be calculated by:[3]

$$h_{system}(t) = \frac{-dR_s(t)}{dt} \times \frac{1}{R\ (t)} \tag{7.3}$$

The mean time to failure ($MTTF_s$) of a hot standby redundant system is calculated by the following equation:[3]

$$MTTF_s = \int_0^\infty R_s(t)dt \tag{7.4}$$

Using equation 7.1 then equation 7.4 becomes:[3]

$$MTTF_s = \int_0^\infty \left\{1 - \prod_{i=1}^{n}[1 - R_i(t)]\right\}dt \tag{7.5}$$

Considering that the time to failure distribution of a component is exponential with mean equal to $\frac{1}{\lambda}$, where λ is the failure rate of the component, as previously explained in the reliability model in Chapter 4, then the $MTTF_s$ of the redundant system can be rewritten, by using equations 7.2 and 7.5:[3]

$$MTTF_s = \int_0^\infty \left\{ 1 - \prod_{i=1}^{n} \left[1 - \exp(-\lambda_i t) \right] \right\} dt \tag{7.6}$$

Considering a wind turbine MTTF of the range 0.25≤MTTF≤1 for the conventional wind turbine system with one converter, then the $MTTF_s$ of the wind turbine with redundant converters could be calculated using equations 7.1 to 7.6 and are presented in tabulated form in Table 7.2. Five different wind turbines system configurations with redundant converter systems have been developed for the investigations in this chapter, that use the redundancy model for different numbers of parallel working converters, i.e. from two up to six redundant converters, as presented in Table 7.2. The calculations of the redundant wind turbine $MTTF_s$ are developed by substituting the converter MTTF of the conventional wind turbine system with the calculated $MTTF_s$ of the redundant converter system. Initial MTTF is termed the wind turbine MTTF using one converter with no redundancy.

Table 7.2 The calculation of the wind turbine $MTTF_s$ for different converter redundancy systems

Initial MTTF	**Wind turbine $MTTF_s$ with converter redundancy (years)**				
Conventional wind turbine system	**2 parallel converters**	**3 parallel converters**	**4 parallel converters**	**5 parallel converters**	**6 parallel converters**
0.25	0.2698	0.2778	0.2848	0.2902	0.2943
0.5	0.5396	0.5556	0.5696	0.5804	0.5886
0.75	0.8094	0.8333	0.8544	0.8706	0.8829
1	1.0791	1.1111	1.1392	1.1608	1.1772

However, it should be mentioned here that the system reliability for large numbers of parallel redundant components should be calculated by a binomial equation for higher calculation accuracy,[3,162] i.e. for more than 4 parallel redundant converters in the wind turbine system then a binomial equation should be considered as it is expected to yield higher accuracy.[163] However, it can be calculated that the percentage difference between the two methods does not exceed 4% when considering 5 or 6 parallel redundant converters,[163] which is considered negligible when considering that the converter system is only a subsystem of the wind turbine and the percentage difference between the two methods does not result in any significant difference in the output results.

An example of the tabulated results presented in Table 7.2 is explained below. Considering a conventional wind turbine system with initial MTTF of 0.25 years using one converter, then applying a hot standby redundancy model to the converter system with two redundant converters and using equation 7.1, then the reliability function $R_{converter}$ of the redundant converter system becomes:

$$R_{converter}(t) = 1 - \prod_{1}^{2}[1 - R_i(t)] = 1 - \left[\left(1 - e^{-\lambda t}\right)\right]^2 = 1 - \left(1 - 2e^{-\lambda t} + e^{-2\lambda t}\right) = 2e^{-\lambda t} - e^{-2\lambda t}$$

Where R_i is the reliability of each redundant converter in the converter system and λ its failure rate, while considering that the failure rate of the two parallel converter modules are equal, since the converter modules should be identical as previously explained in paragraph 7.2.2 in this Chapter (p. 274-279). Now considering equation 7.3 and the $R_{converter}$ as calculated above, then the failure rate function of the redundant converter system becomes:

$$h_{converter}(t) = -\frac{d\left(2e^{-\lambda t} - e^{-2\lambda t}\right)}{dt} \times \frac{1}{2e^{-\lambda t} - e^{-2\lambda t}} = \frac{2\lambda e^{-2\lambda t} + 2\lambda e^{-\lambda t}}{2e^{-\lambda t} + e^{-2\lambda t}} \qquad (7.7)$$

Now considering that the converter system of the wind turbine accounts for 22% of the total system failure rate, as explained earlier in this Chapter, then the failure rate of the redundant converter system can be calculated using the failure rate function presented above while considering time t for one year:

$$h_{converter} = 0.592$$

Having calculated the new converter system failure rate, then the failure rate of the total wind turbine system and in turn its $MTTF_s$ can be calculated as presented in Table 7.2. Similarly the $MTTF_s$ of the wind turbine for the other redundancy models, e.g. three parallel converter modules, can be calculated using the same technique as detailed above.

The calculated wind turbine $MTTF_s$ of the different wind turbine redundancy systems presented in Table 7.2 are used to investigate the effect of the hot standby redundancy model on the wind farm availability, cumulative energy output, LPC of energy and CO2 emissions, when employing the planned intervention maintenance policy.

7.4 Case study 1 – London Array offshore wind farm

Table 7.3 gives the input parameters of the London Array offshore wind farm, which were used to employ the planned intervention maintenance policy (PM 2) in order to determine the effects of the hot standby redundancy on the wind turbine converter system. Six different wind turbine system configurations have been investigated for this case study (see Table 7.2) having different converter system designs, i.e. from one up to six parallel working converters.

Table 7.3 London Array offshore wind farm parameters.[92]

Parameters	Value
Turbine Power rating	3.6 MW (Siemens)
Number of Turbines	175
Economic lifetime of project	20 years
Capacity factor	45%
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Capital Investment cost	1.96 billion pounds
Converter design	6 different investigated
Cost of conventional converter	100,000 pounds (for 3 MW power load)

7.4.1 The effect of redundancy on the wind turbine MTTF

Considering wind turbine MTTF versus the number of redundant converters in Figure 7.5, then the four graphs representing different initial wind turbine MTTF, i.e. as presented in Table 7.2 for the conventional wind turbine system, show that the number of wind turbine redundant converters affect the wind turbine MTTF as expected from the development of the hot standby redundancy model, since an increase in the number of redundant converters would result in increased wind turbine MTTF. The results have been simulated using the 'PM 2' scenario of the planned intervention maintenance policy. The number of redundant converters indicates the design of the wind turbine system, i.e. the number of added parallel working converters in the wind turbine system, as previously explained in this Chapter.

The four graphs presented in Figure 7.5 show a graphical representation of the calculated values of $MTTF_S$ as seen in their tabulated form in Table 7.2 for the range of initial wind turbine MTTF of $0.25 \leq MTTF \leq 1$, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). When considering the number of redundant converters of one, x-axis of the graphs in Figure 7.5, then this represents a wind turbine system with no redundancy applied on the converter system, i.e. the conventional wind turbine system with one converter serving the total wind turbine power load. It should be mentioned at this point that the x-axis only receives non-negative integer numbers, i.e. '$\text{Re}\,dundant\ Converters \in Z^{+}$', which indicates that there are no values on the x-axis between one and two or between two and three etc. For this reason the curve fitting tool of Mathworks Matlab software package has been used to develop curves that follow the scatter plots (different points on each graph between x and y axis). These scatter plots are named for each graph presented in the following paragraphs and the mathematical form of the developed curves are presented on the legend of each graph.

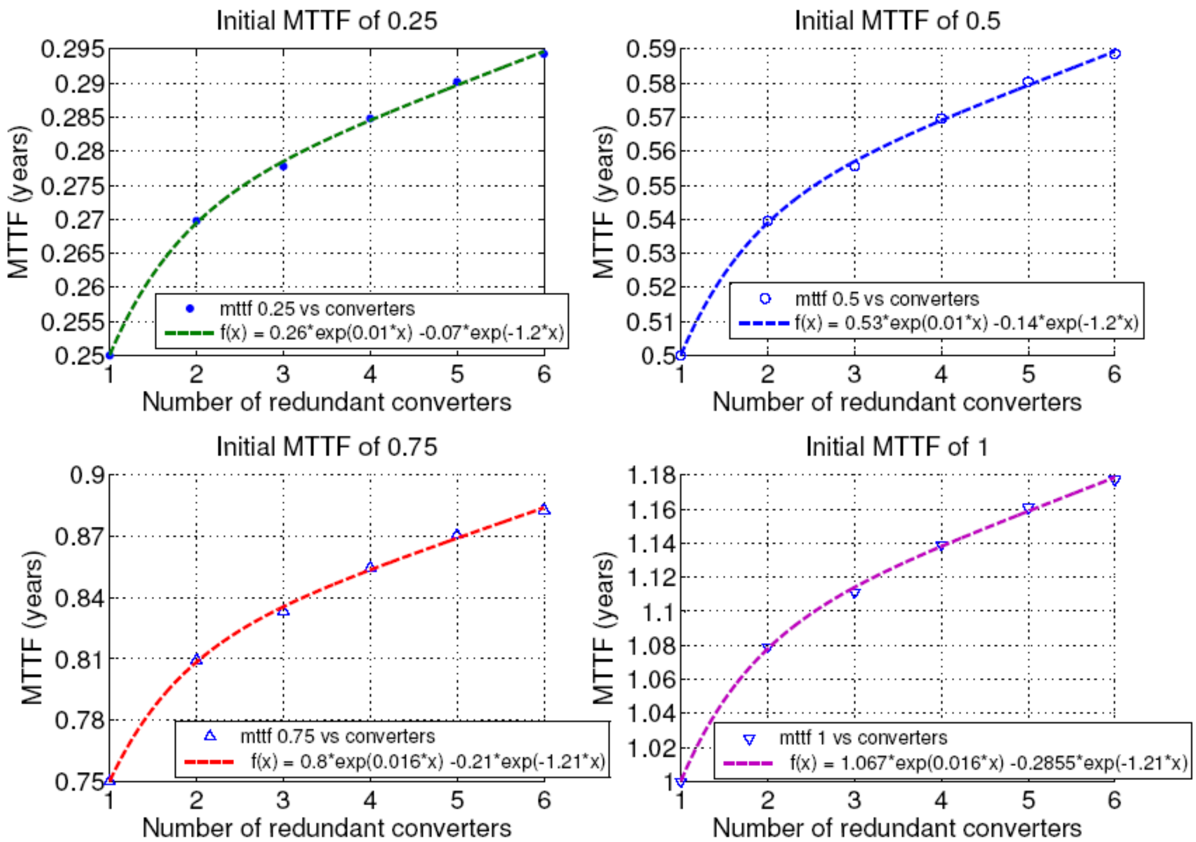

Figure 7.5 The effect of the hot standby redundancy model of the wind turbine converter system on the wind turbine MTTF. The x-axis gives the different wind turbine converter redundancies, i.e. the different wind turbine converter designs as detailed in Table 7.2. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

It could be observed in Figure 7.5 that the wind turbine MTTF increases for increasing number of redundant converters, as would be expected from the redundancy model developed in equations 7.2 to 7.6 previously explained in the development of the hot standby redundancy model paragraph. The nature of the four curves of wind turbine MTTF against the number of redundant converters is given by equation 7.6. For example when using equation 7.6 to calculate the wind turbine $MTTF_s$ by applying a redundancy model of two parallel converter systems, then takes the form of equation 7.7, as previously explained for the development of the hot standby redundancy model.

7.4.2 The effect of redundancy on the wind farm availability

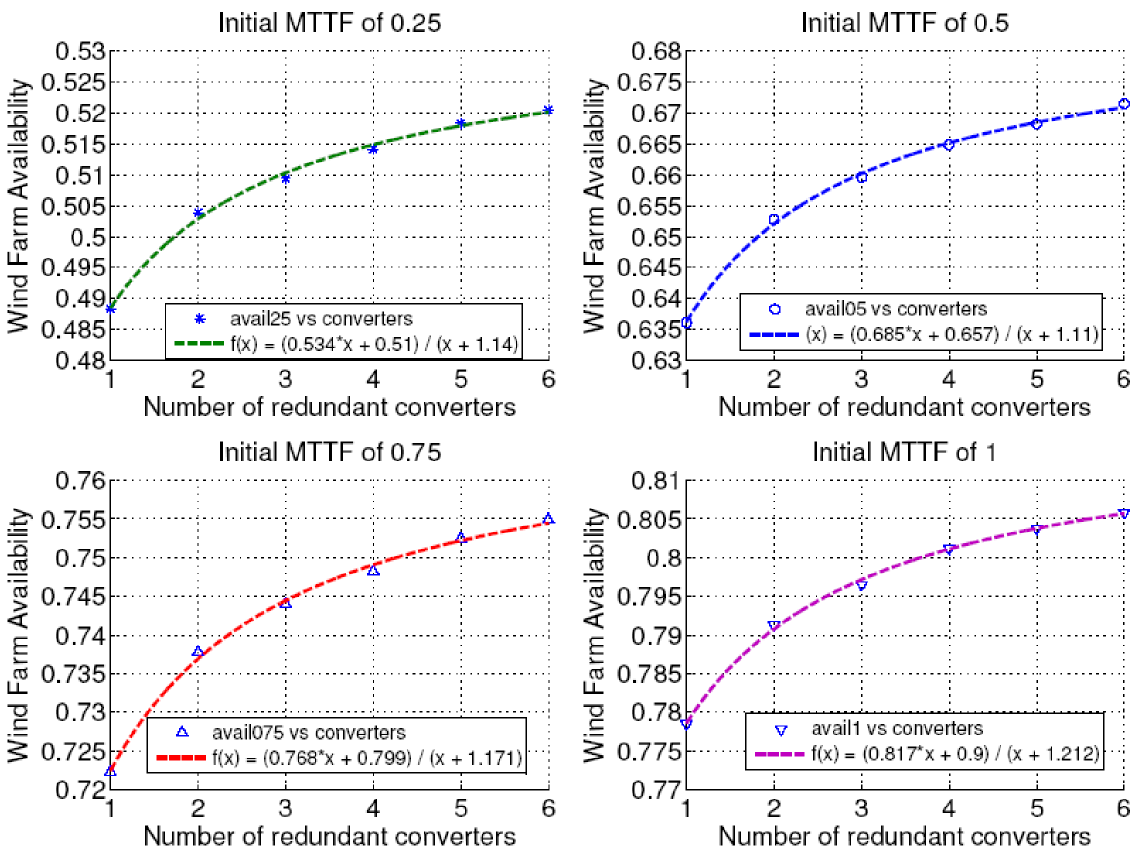

Figure 7.6 The effect of the hot standby redundancy model of the wind turbine converter system on the wind farm availability. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

Considering the wind farm availability versus the number of redundant converters presented in Figure 7.6, then the four graphs representing different initial wind turbine MTTF, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple), show that the number of wind turbine redundant converters affect the wind farm availability as expected from the development of the hot standby redundancy model, since an increase in the number of redundant converters would result in increased wind turbine MTTF levels and in turn in increased wind farm availability, as previously explained for the case studies of offshore wind farms presented in Chapters 5 and 6. All curves are parabolic in their nature (side-opening parabola), the reason being the relationship between wind turbine availability and wind turbine MTTF, as previously explained in equation 4.12 for the Monte Carlo model in Chapter 4 (p. 114).

7.4.3 The effect of redundancy on the number of failures

Considering the number of failures supported by helicopters versus the number of redundant converters, as presented in Figure 7.7, then the four graphs representing different initial wind turbine MTTF, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple), show that the number of wind turbine redundant converters affects the number of failures as expected from the development of the hot standby redundancy model, since the offshore wind farm will experience less failures resulting in total wind turbine power loss. It should be mentioned at this point that only the number of failures supported by helicopters is considered, since the wind turbine converter failures are maintained using helicopters, as previously detailed in Chapter 4.

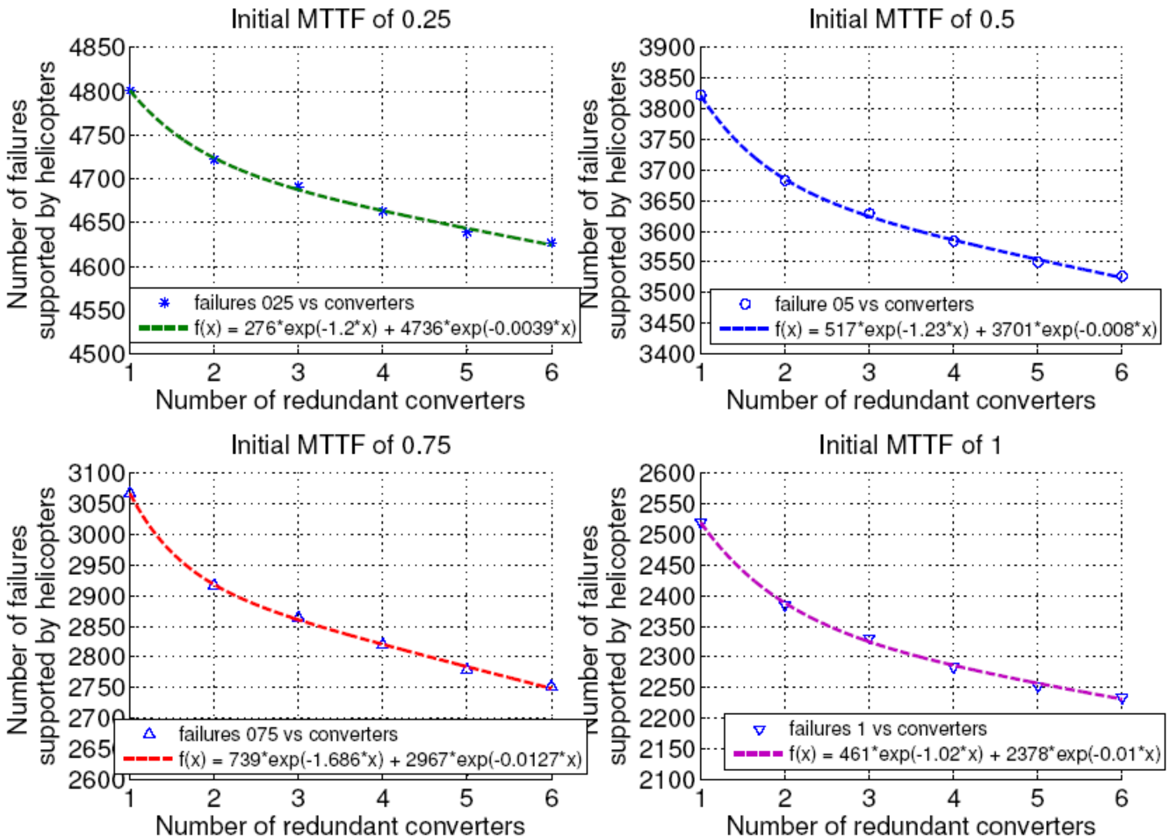

Figure 7.7 The effect of the hot standby redundancy model of the wind turbine converter system on the number of failures supported by helicopters. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

7.4.4 The effect of redundancy on the energy output

Figure 7.8 shows the effect of the hot standby redundancy model of the wind turbine converter system on the cumulative energy output. The four graphs in Figure 7.8 represent the four different initial wind turbine MTTF levels that have been simulated for the 'PM 2' scenario of the planned intervention maintenance policy, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The four curves in Figure 7.8 show that the number of redundant converters affects the energy output as would be expected, since an increase in the number of redundant converters would result in increased wind farm availability, as explained earlier for Figure 7.6, which in turn would result in increased energy output, this being explained previously in Chapter 4. Again, the four curves are each parabolic in nature (side-opening parabola), this being explained because the relationship between the cumulative energy output and wind farm availability is linear, as previously explained for equation 4.9 in Chapter 4 (p. 110), consequently the relationship between the energy output and wind turbine MTTF is also parabolic, as previously described for equations 4.12 (p. 119) and 5.1 (p. 146) in Chapters 4 and 5 respectively.

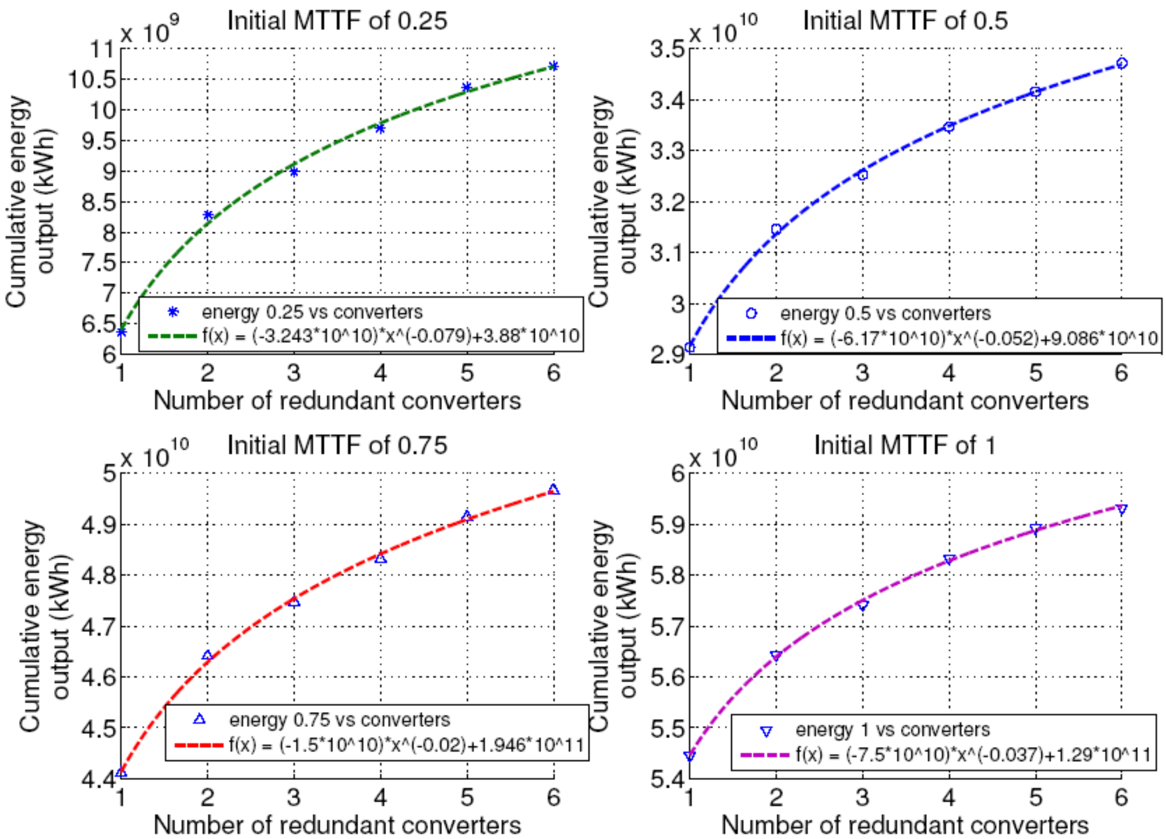

Figure 7.8 The effect of the hot standby redundancy model of the wind turbine converter system on the cumulative energy output. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

An important observation made from the results presented in Figure 7.8 is the effect of the increase of wind turbine redundant MTTF on the cumulative energy output, e.g. considering an initial MTTF of 0.25 years, then the extra energy achieved using 6 redundant converter modules is 62.2% increased, as compared to the conventional wind turbine system, whilst considering an initial MTTF of 1 years, then the extra energy achieved is 8.8%. This significant observation indicates that the higher the initial wind turbine MTTF is then the lower the effect of the redundancy model on the cumulative energy output becomes.

The extra energy achieved results from the hot standby redundancy model applied on the converter system of the wind turbine, i.e. when a failure is detected on one of the parallel converter systems then the wind turbine continues to be operational only at reduced power output, as previously explained for paragraph 7.2.2 earlier in this Chapter. It is important to mention here that when employing the ‘PM 2’ scenario the wind farm is visited twice a year for repairs and maintenance on the wind turbines, which indicates that even when applying a redundancy model, all the parallel converter systems on the wind turbine could potentially fail before the next maintenance visit, resulting in the wind turbine to stop producing energy, while also other wind turbine components could have failed even before all the parallel converter modules fail. This observation has been considered for the redundancy model developed for this study, when calculating the extra energy output gained from the converter redundancy by using the equations presented for the reliability model in Chapter 4 and the equations presented in the hot standby redundancy model earlier in this Chapter.

7.4.5 The effect of redundancy on the LPC of energy

Figure 7.9 shows the effect of the redundancy of the wind turbine converter system on the LPC of energy. The four graphs in Figure 7.9 represent the four different initial wind turbine MTTF levels that have been simulated for the ‘PM 2’ scenario of the planned intervention maintenance policy, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The four curves in Figure 7.9 show that the number of redundant converters affects the LPC of energy as would be expected, since an increase in the number of redundant converters would result in increased wind farm availability, as explained earlier for Figure 7.6, which in turn would give increased energy output which results in decreased LPC of energy, this being explained previously in Chapter 4 for the economic model (p. 105). The four curves presented in Figure 7.9 are each equilateral (rectangular) hyperbolic in nature, this being explained by the fact that the LPC of energy is proportional to the inversed value of energy output, according to equation 4.8, as previously presented for the economic model in Chapter 4 (p.105).

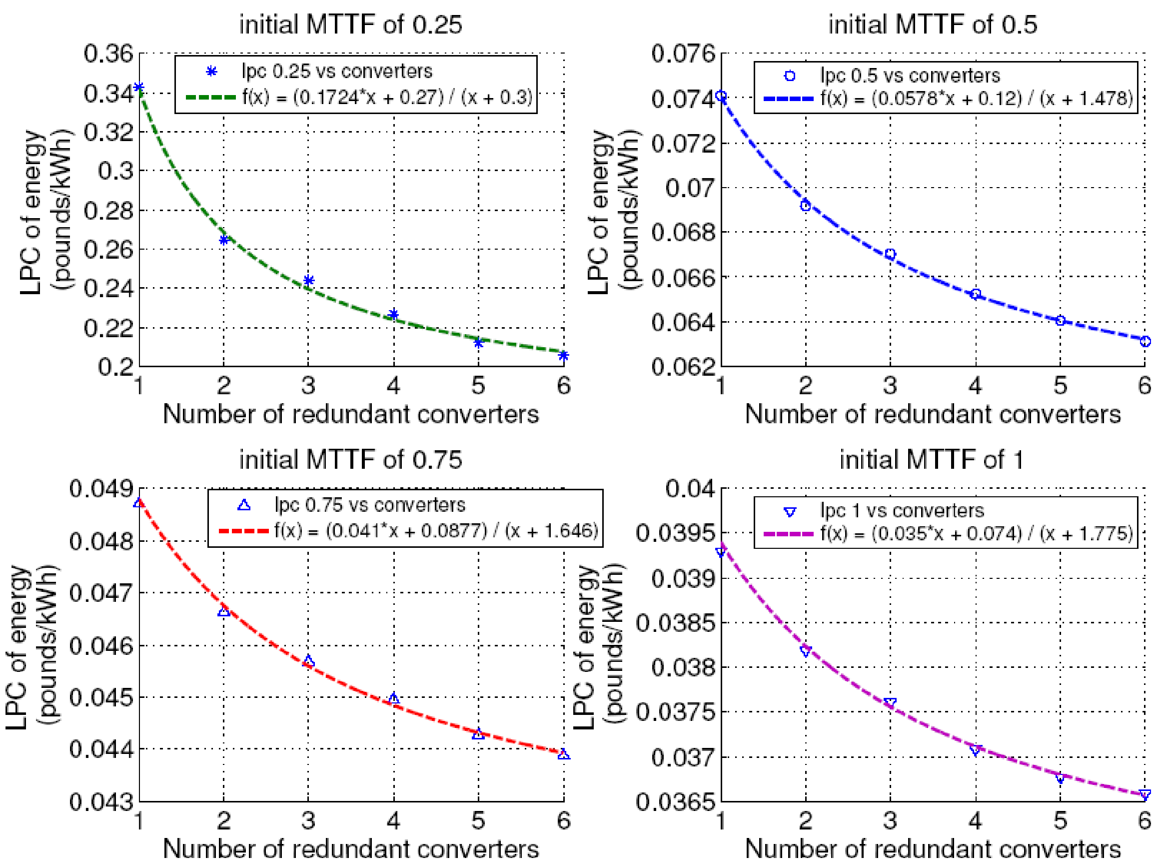

Figure 7.9 The effect of the hot standby redundancy model of the wind turbine converter system on the LPC of energy. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

It is important to mention at this point that when applying the redundancy model on the wind turbine converter system, results in different initial cost of the wind turbine, which has been simulated by adding the cost of the extra redundant converters to the CAPEX of the wind farm, while also considering the extra cost that results from a redundancy model on the generator and transformer of the wind turbine, as discussed earlier in this chapter (p. 278). The cost of the conventional converter system has been obtained by a study on the cost of different wind turbine systems,[119] while the cost of each additional redundant converter to the system is calculated from interpolating the converter output with the relative cost of the converter using the curve given in Figure 7.4. It should also be mentioned that the maintenance costs of the extra redundant converters are also considered when simulating the calculation of the maintenance costs for the OPEX, as previously explained in Chapter 4.

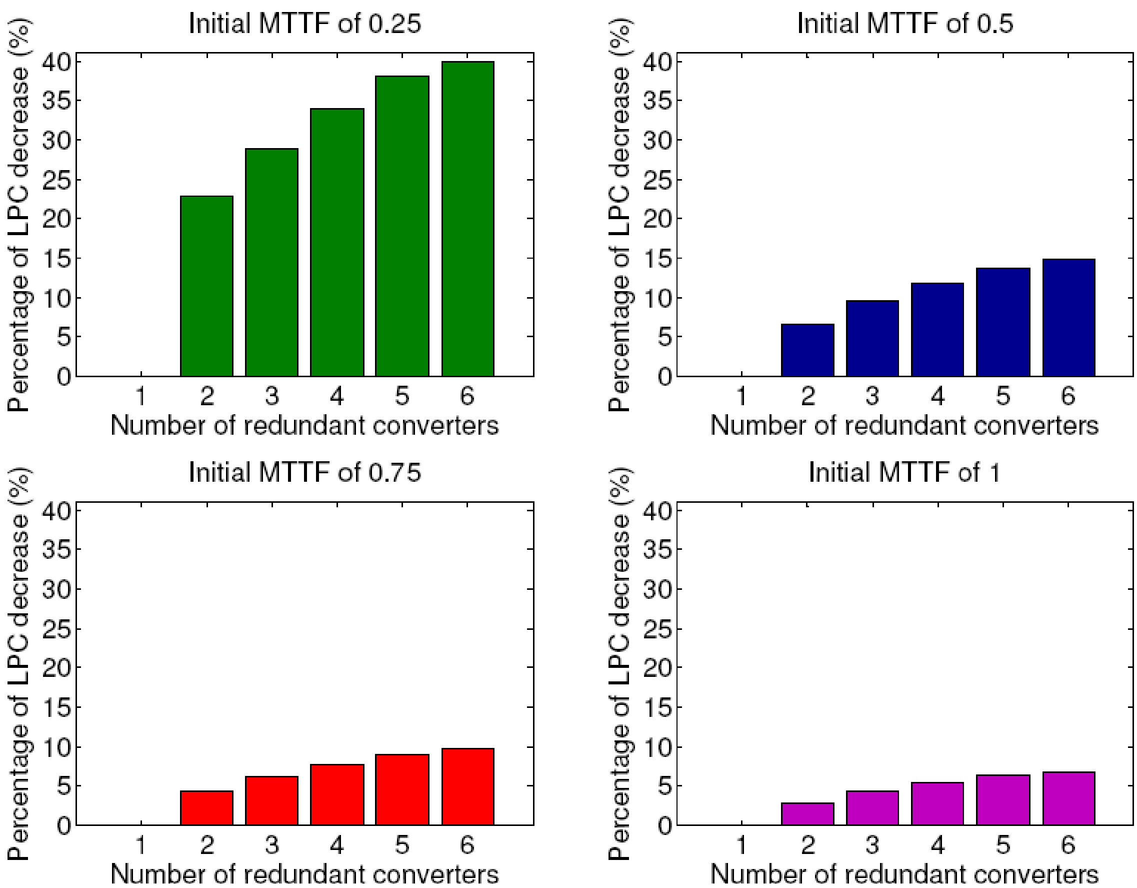

Figure 7.10 The effect of the hot standby redundancy model of the wind turbine converter system on the percentage decrease of the LPC of energy. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

An important observation made from the results presented in Figure 7.9 is the effect of the increase of wind turbine redundant MTTF on the LPC of energy, e.g. considering an initial MTTF of 0.25 the reduction of LPC of energy achieved using 6 redundant converter modules is 39.9%, as compared to the conventional wind turbine system, whilst considering an initial MTTF of 1 the reduction of LPC of energy achieved is 6%. The above observation indicates that the higher the initial wind turbine MTTF is, then the lower the effect of the redundancy model on the LPC of energy becomes.

The above conclusions on the results are presented in detail in Figure 7.10, where the percentage decrease of the LPC of energy is plotted against the number of redundant converters for different initial wind turbine MTTF values, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). It can be observed in Figure 7.10 that the higher the initial wind turbine MTTF becomes, then the lower is the effect of extra redundant converters on the LPC of energy achieved. For example, considering an initial wind turbine MTTF of 0.25 years then the rate of change of the percentage decrease of the LPC of energy is significantly higher, as compared to the results obtained for initial wind turbine MTTF of 1 year.

7.4.6 The effect of redundancy on the CO2 emissions

Figure 7.11 gives the effect of the redundancy of the wind turbine converter system on the CO2 emissions due to maintenance expeditions. The four graphs in Figure 7.11 present the four different initial wind turbine MTTF levels that have been simulated for the ‘PM 2’ scenario of the planned intervention maintenance policy, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The four curves in Figure 7.11 show that the number of redundant converters affects the CO2 emissions due to maintenance as would be expected, since an increase in the number of redundant converters would result in decrease of the number of wind turbine failures as previously explained for Figure 7.7, and in turn will result in decrease of CO2 emissions.

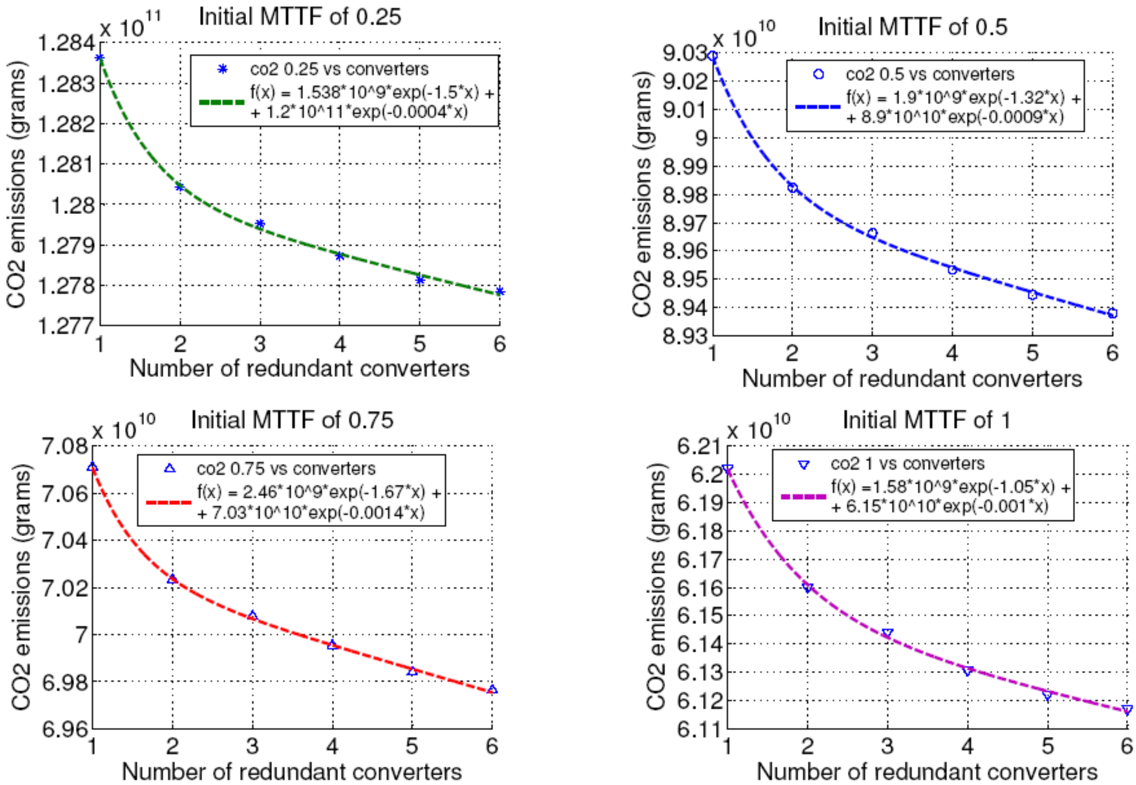

Figure 7.11 The effect of the hot standby redundancy model of the wind turbine converter system on the CO2 emissions. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

The four curves presented in Figure 7.11 are each equilateral (rectangular) hyperbolic in nature, this being explained because the CO2 emissions and the number of wind turbine failures are proportional, as explained in Appendix I. An important observation of the results presented in Figure 7.11 is that the higher the initial wind turbine MTTF is, then the lower the effect of the redundancy model on the CO2 emissions becomes.

7.4.7 The effect of redundancy on the cost of wind turbines

Figure 7.12 shows the cost of each wind turbine of the London Array offshore wind farm when increasing the level of redundancy for the converter system and the percentage of increase of the wind turbine cost, all plotted against the number of redundant converters. The cost of each wind turbine is calculated by dividing the CAPEX with the total number of wind turbines in the London Array offshore wind farm, where the CAPEX is calculated by adding to the initial CAPEX, i.e. the CAPEX of the wind farm with no redundancy scheme, with the cost of each added redundant converter for each wind turbine, and the extra costs incurred for the generator and transformer for the redundant system, as previously explained for Figure 7.9.

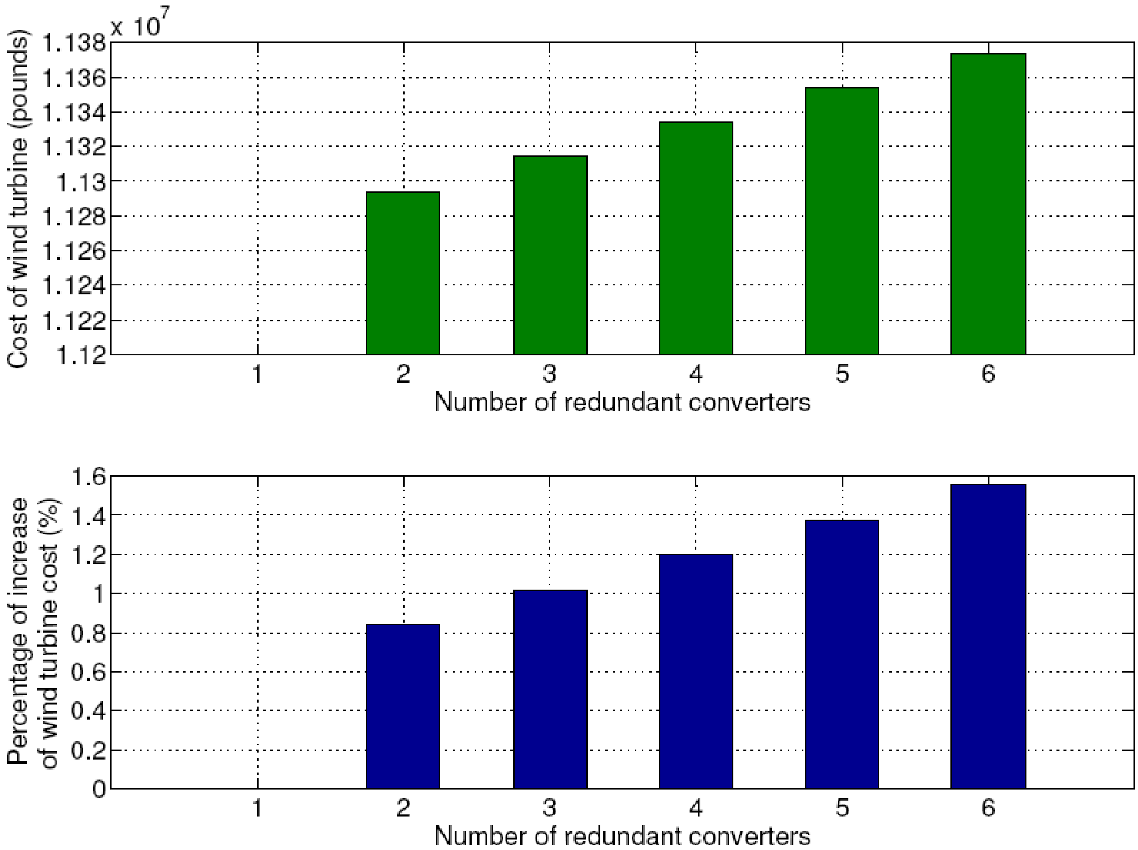

Figure 7.12 The effect of the redundancy model of the wind turbine converter system on the cost per wind turbine and the percentage of increase of the wind turbine cost. The results are simulated using the 'PM 2' scenario for the London Array offshore wind farm.

Considering the cost of each installed wind turbine for the London Array offshore wind farm with no converter redundancy is 11.2 million pounds, which is increased up to 11.4 million per installed wind turbine for six parallel converter systems. What is interesting to observe in Figure 7.12 is that despite the increase in the cost of each wind turbine for increasing number of redundant converters in the system, the percentage of increase of the wind turbine cost does not exceed 1.6%, as compared to the conventional wind turbine system with no redundancy, which indicates that the cost of adding redundant converters to the wind turbine system and the cost of their maintenance has a small effect, as compared to the very high cost of each installed wind turbine.

7.5 Case study 2 – Kentish Flats offshore wind farm

The Kentish Flats offshore wind farm is located in the UK at the Thames Estuary which is online since 2005 feeding the national grid. Table 7.4 shows the input parameters of the Kentish Flats offshore wind farm, which were used to employ the planned intervention maintenance policy, ‘PM 2’, in order to determine the effects of the redundancy of the wind turbine converter system. Six different wind turbine system configurations have been investigated for this case study (see Table 7.2) having different converter system designs, i.e. from one up to six parallel working converters.

Table 7.4 Kentish Flats offshore wind farm parameters.[94,95]

Parameters	**Value**
Turbine Power rating	3 MW
Number of Turbines	30
Distance to shore	10 km
Capacity factor	35%
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Capital Investment cost	105 million pounds
Cost of conventional converter	100,000 pounds (for 3 MW power load)

Figure 7.13 shows the effect of the redundancy of the wind turbine converter system on the LPC of energy for the Kentish Flats offshore wind farm. The four graphs in Figure 7.13 represent the four different initial wind turbine MTTF levels that have been simulated for the ‘PM 2’ scenario of the planned intervention maintenance policy, i.e.

for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The four curves in Figure 7.13 show that the number of redundant converters affects the LPC of energy as would be expected, since an increase in the number of redundant converters would result in increased wind farm availability, as previously explained for Figure 7.6, which in turn would give increased energy output which results in decreased LPC of energy, this being explained previously in Chapter 4. The four curves presented in Figure 7.13 are each equilateral (rectangular) hyperbolic in nature, this being explained because the LPC of energy is proportional to the inversed value of energy output, according to equation 4.8, as previously presented for the economic model in Chapter 4 (p. 105).

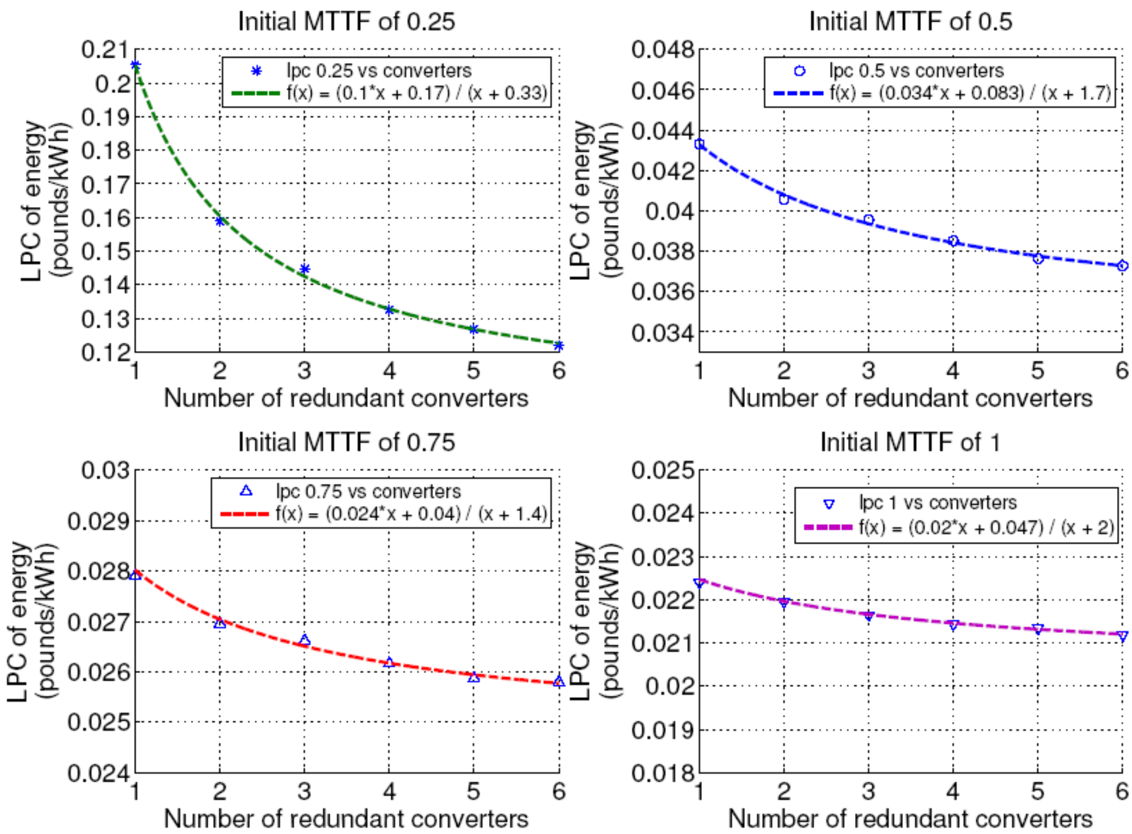

Figure 7.13 The effect of the hot standby redundancy model of the wind turbine converter system on the LPC of energy. The results are simulated using the 'PM 2' scenario for the Kentish Flats offshore wind farm.

It is important to mention at this point that the cost of each added redundant converter to the wind turbine system and the increase in the generator and transformer costs have been considered and calculated using the same technique as previously done in this Chapter for the London Array offshore wind farm case study. It should also be mentioned that the maintenance costs of the extra redundant converters are also considered when simulating the calculation of the maintenance costs for the OPEX, as explained in Chapter 4.

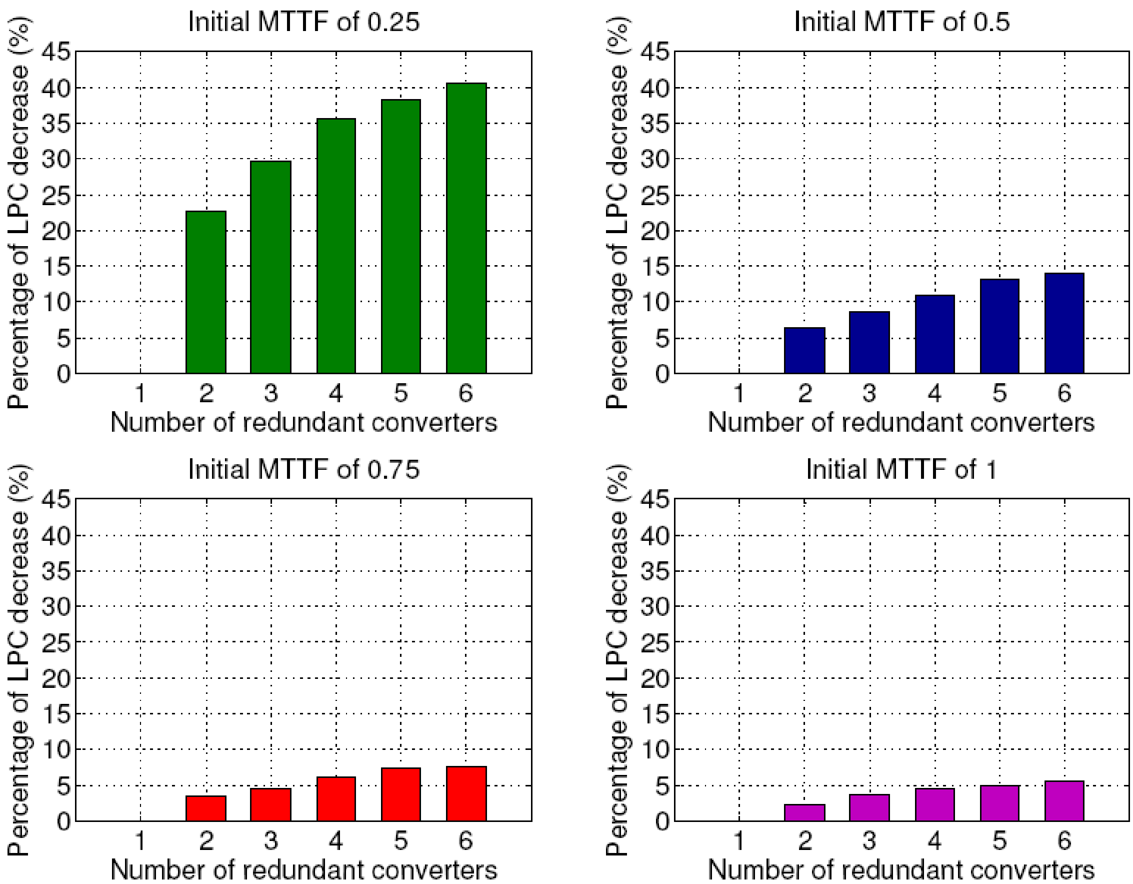

Figure 7.14 The effect of the hot standby redundancy model of the wind turbine converter system on the percentage decrease of the LPC of energy. The results are simulated using the 'PM 2' scenario for the Kentish Flats offshore wind farm.

An important observation made from the results presented in Figure 7.13 is the effect of the increase of wind turbine redundant MTTF on the LPC of energy, e.g. considering an initial wind turbine MTTF of 0.25 years, then the reduction of LPC of energy achieved using 6 redundant converter modules is 40.6%, as compared to the conventional wind turbine system, whilst considering an initial MTTF of 1 year, then the reduction of LPC of energy achieved is 5%. The above observation indicates that the higher the initial wind turbine MTTF is then the lower the effect of the redundancy model on the LPC of energy becomes. It could also be concluded from the results presented in Figure 7.13 that for wind turbine MTTF of 0.5 years and above, the redundancy model does not achieve any significant decrease in the cost of the LPC of energy.

The conclusions drawn from the results shown in Figure 7.13 are presented in detail in Figure 7.14, where the percentage decrease of the LPC of energy is plotted against the number of redundant converters for different initial wind turbine MTTF values, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The results presented in Figure 7.14 show that the higher the wind turbine MTTF becomes then the lower the effect of the redundancy model on the LPC of energy.

Figure 7.15 shows the cost of each wind turbine of the Kentish Flats offshore wind farm when increasing the level of redundancy for the converter system and the percentage of increase of the wind turbine cost, all plotted against the number of redundant converters. The cost of each wind turbine is calculated by dividing the CAPEX with the total number of wind turbines in the Kentish Flats offshore wind farm, where the CAPEX is calculated by adding to the initial CAPEX, i.e. the CAPEX of the wind farm with no redundancy, with the cost of each added redundant converter for each wind turbine. The cost of each installed wind turbine for the Kentish Flats offshore wind farm with no redundancy scheme is 3.5 million pounds and this value is increased up to 3.65 million pounds per installed wind turbine for six parallel converter modules. When comparing this value with the London Array offshore wind farm (11.2 millions pounds) it can be observed that it is significantly lower, which can be explained by the significant difference in the distance to shore and water depth, as compared to the London Array offshore wind farm, which highly affects the CAPEX of the project.

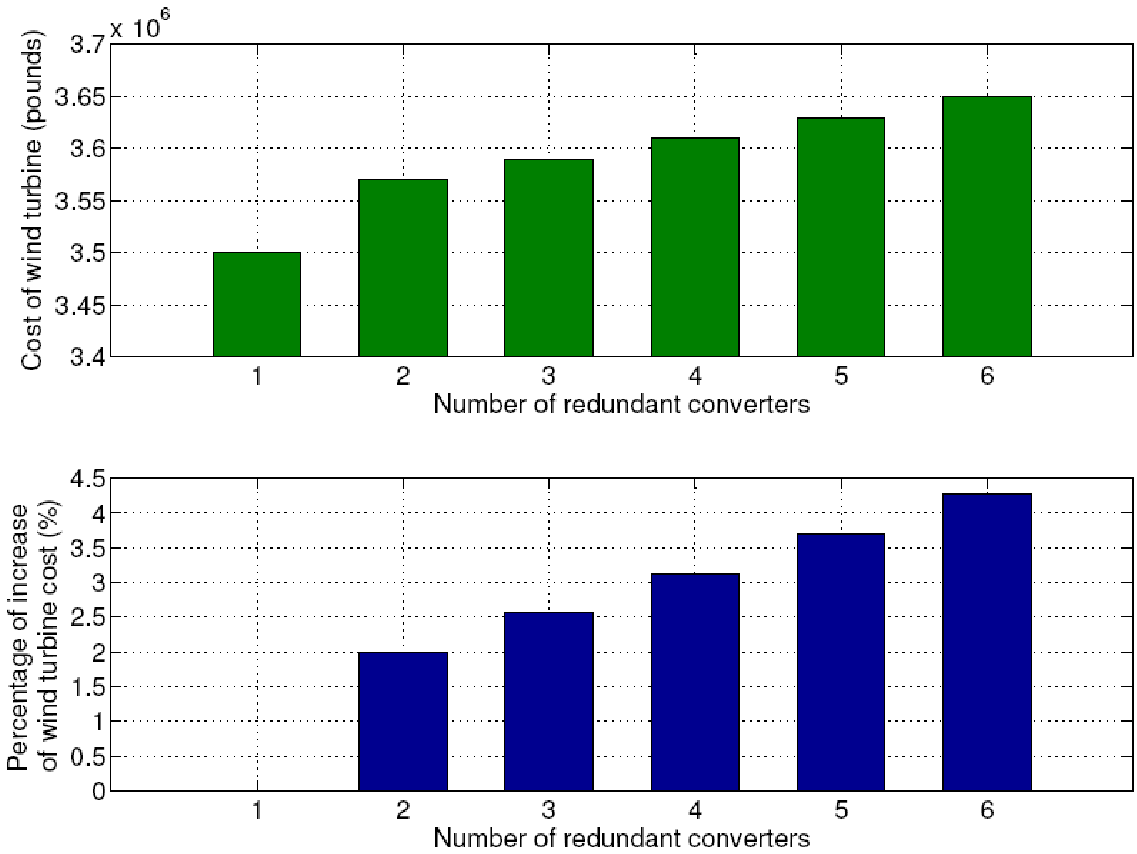

Figure 7.15 The effect of the redundancy model of the wind turbine converter system on the cost per wind turbine and the percentage of increase of the wind turbine cost. The results are simulated using the 'PM 2' scenario for the Kentish Flats offshore wind farm.

The above observation can be justified by the percentage of increase of wind turbine cost for increasing the number of redundant converters, which can reach up to 4.5%, as shown in Figure 7.15, which is found to be significantly higher as compared to the results presented in Figure 7.12 for the London Array offshore wind farm. These results indicate that the cost of adding redundant converters to the wind turbine system affects significantly the CAPEX of the Kentish Flats offshore wind farm, as compared to the London Array offshore wind farm, which in turn results in a lower effect of the redundancy model on the LPC of energy.

7.6 Case study 3 – DOWEC offshore wind farm

The DOWEC (Dutch Offshore Wind Energy Converter) project investigated the different input costs and LPC of energy for a 480 MW offshore wind farm consisting of 80 offshore wind turbines of 6 MW of rating, which is planned to be constructed in the future in the North Sea at a location known as 'NL7'.[70,71] Table 7.5 shows the input parameters of the DOWEC offshore wind farm, which were used to employ the planned intervention maintenance policy, 'PM 2', in order to determine the effects of the redundancy of the wind turbine converter system. Six different wind turbine system configurations have been investigated for this case study (see Table 7.2) having different converter system designs, i.e. from one up to six parallel working converters.

Table 7.5 DOWEC project parameters.[70,71]

Parameters	Value
Turbine Power rating	6 MW
Number of Turbines	80
Distance to shore	100 km
Capacity factor	43%
Mean time to repair	1.5 days
Mean time for preventive maintenance	1 day
Capital Investment cost	701 million euros
Cost of each added converter	100,000 pounds (for 3 MW power load)

Figure 7.16 shows the effect of the redundancy of the wind turbine converter system on the LPC of energy for the DOWEC offshore wind farm. The four graphs in Figure 7.16 represent the four different initial wind turbine MTTF levels that have been simulated for the 'PM 2' scenario of the planned intervention maintenance policy, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The four curves in Figure 7.16 show that the number of redundant converters affects the LPC of energy as would be expected, since an increase in the number of redundant converters would result in increased wind farm availability, as previously explained for

Figure 7.6, which in turn would give increased energy output which results in decreased LPC of energy, this being explained previously in Chapter 4. The four curves presented in Figure 7.16 are each equilateral (rectangular) hyperbolic in nature, this being explained because the LPC of energy is proportional to the inversed value of energy output, according to equation 4.8 (p. 105 - 110).

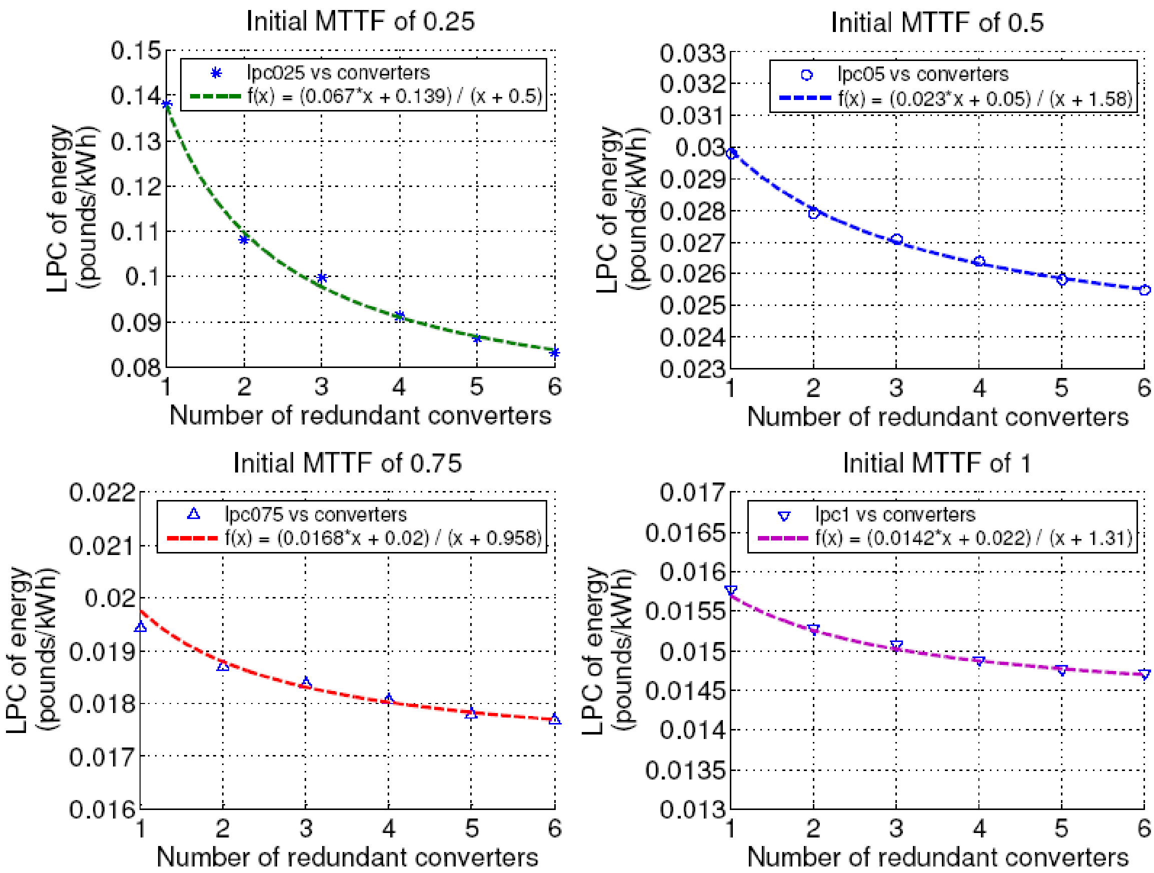

Figure 7.16 The effect of the hot standby redundancy model of the wind turbine converter system on the LPC of energy. The results are simulated using the 'PM 2' scenario for the DOWEC offshore wind farm.

It is important to mention at this point that the cost of each added redundant converter to the wind turbine system and the increase in the generator and transformer costs have been calculated using the same technique as previously performed in this Chapter for the London Array offshore wind farm case study. It should be mentioned that the maintenance costs of the extra redundant converters are also considered when simulating the calculation of the maintenance costs for the OPEX, as explained in Chapter 4.

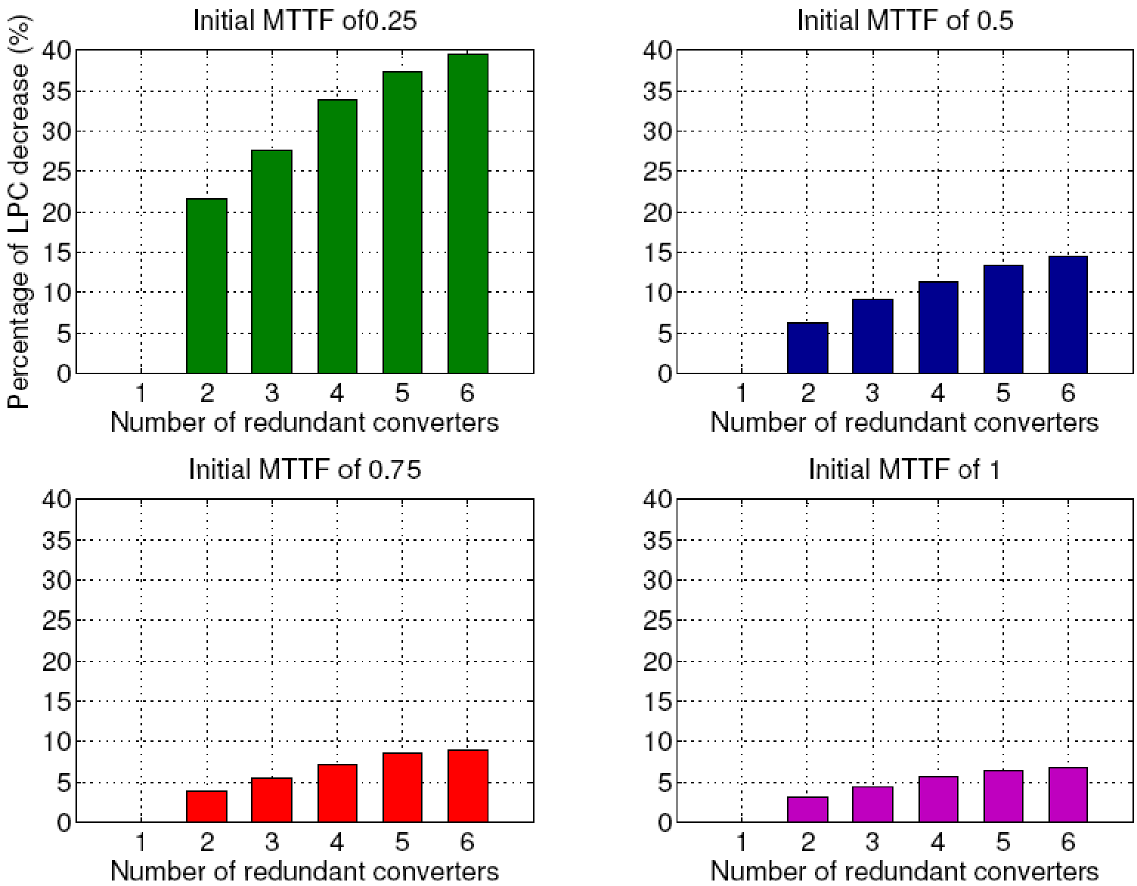

Figure 7.17 The effect of the hot standby redundancy model of the wind turbine converter system on the percentage decrease of the LPC of energy. The results are simulated using the 'PM 2' scenario for the DOWEC offshore wind farm.

An important observation made from the results presented in Figure 7.16 is the effect of the increase of wind turbine redundant MTTF on the LPC of energy, e.g. considering an initial MTTF of 0.25 years, then the reduction of LPC of energy achieved using 6 redundant converter modules is 40%, as compared to the conventional wind turbine system, whilst considering an initial MTTF of 1 year, then the reduction of LPC of energy achieved is 5.5%. The above observations indicate that the higher the initial wind turbine MTTF is then the lower the effect of the redundancy model on the LPC of energy becomes. It could also be concluded from the results presented in Figure 7.16

that for wind turbine MTTF of 0.75 years and above, the redundancy model does not achieve any significant decrease in the cost of the LPC of energy.

The conclusions drawn from the results shown in Figure 7.16 are presented in detail in Figure 7.17, where the percentage decrease of the LPC of energy is plotted against the number of redundant converters for different initial wind turbine MTTF values, i.e. for MTTF=0.25 (green), MTTF=0.5 (blue), MTTF=0.75 (red) and MTTF=1 (purple). The results presented in Figure 7.17 show that the higher the wind turbine MTTF becomes then the lower the effect of the redundancy model on the LPC of energy.

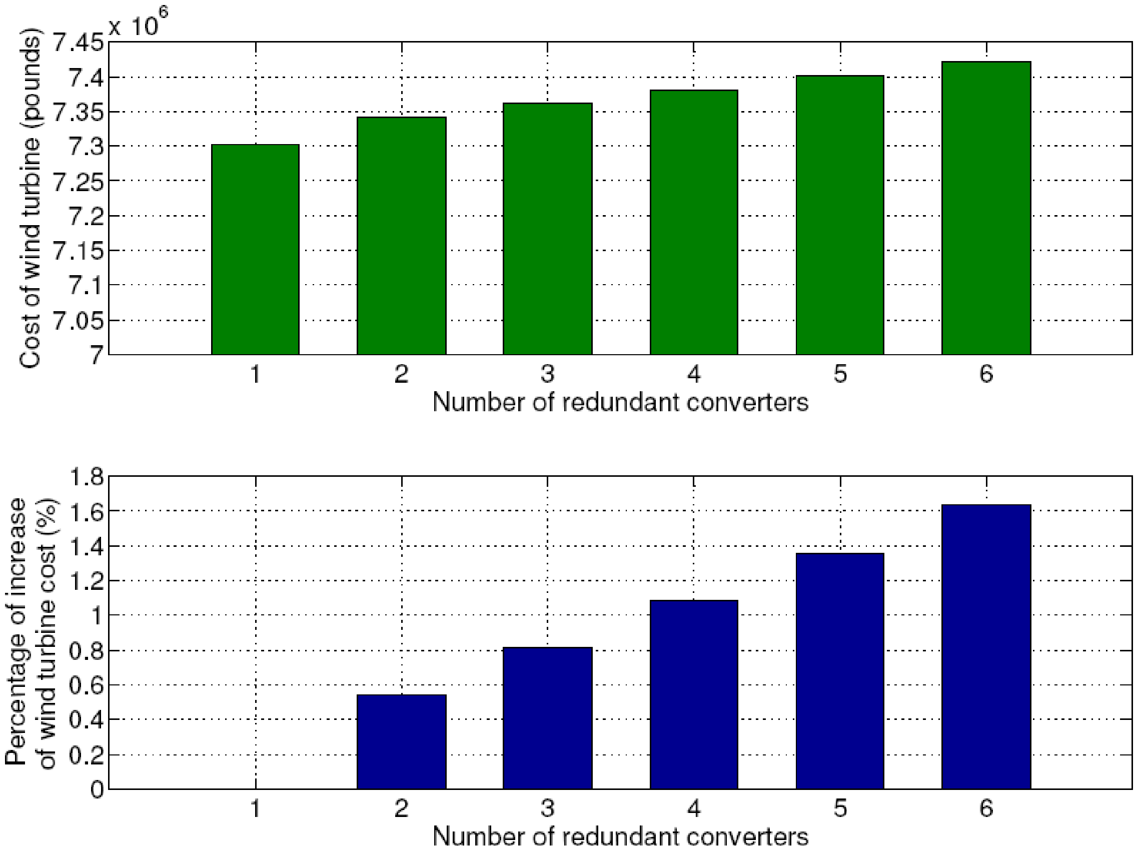

Figure 7.18 The effect of the redundancy model of the wind turbine converter system on the cost per wind turbine and the percentage of increase of the wind turbine cost. The results are simulated using the 'PM 2' scenario for the DOWEC offshore wind farm.

Figure 7.18 shows the cost of each wind turbine of the DOWEC offshore wind farm when increasing the level of redundancy for the converter system and the percentage of increase of the wind turbine cost, all plotted against the number of redundant converters. The cost of each wind turbine is calculated by dividing the CAPEX with the total number of wind turbines in the DOWEC offshore wind farm, where the CAPEX is calculated by adding to the initial CAPEX, i.e. the CAPEX of the wind farm with no redundancy, the cost of each added redundant converter for each wind turbine. The cost of each installed wind turbine for the DOWEC offshore wind farm with no redundancy scheme is 7.3 million pounds and this value is increased up to 7.43 million pounds per installed wind turbine for six parallel converter systems. When comparing this value with the London Array offshore wind farm (11.2 millions pounds) it is found to be lower, while it is found to be significantly higher as compared to the Kentish Flats offshore wind farm. The above observation can be justified by the percentage of increase of wind turbine cost for increasing the number of redundant converters, which can reach up to 1.67%, as shown in Figure 7.18, which is found to be higher as compared to the results presented in Figure 7.8 for the London Array offshore wind farm.

7.7 Comparison of results

The results obtained when applying a hot standby redundancy model on the wind turbine converter system for three offshore wind farm case studies; London Array, Kentish Flats and DOWEC, were presented in this Chapter. These results are summarised in Tables 7.6 and 7.7, in order to compare them for the different case studies investigated.

Considering Table 7.6, the results obtained are divided into four sections for the different initial wind turbine MTTF investigated, while for each of these initial MTTF the maximum number of redundant converters needed to achieve a significant decrease in the LPC of energy is reported for all the case studies investigated in this Chapter.

Now considering the London Array offshore wind farm case study, the use of all six parallel converter modules can be justified across the range of initial MTTF, i.e. 0.25≤MTTF≤1, whilst from the results obtained for the other two offshore wind farm case studies investigated, i.e. Kentish Flats and DOWEC project, the maximum number of redundant converters needed to achieve a significant reduction in the LPC of energy is considerably lower. It can be observed in Table 7.6 that for the Kentish Flats offshore wind farm case study a hot standby redundancy model on the converter system would not yield any significant reduction in the LPC of energy when considering initial wind turbine MTTF above 0.5 years. This indicates that the redundancy model on the wind turbine converter system has a lower effect on the LPC of energy achieved, this being explained by the fact that the costs associated with the added converters on the wind turbine system and the costs associated with their maintenance along with the extra costs incurred for a multi-phase generator and transformer greatly affect the economics of the project, despite the higher energy output that is achieved. The same observations could be made for the DOWEC offshore wind farm case study when considering initial wind turbine MTTF above 0.75 years. The reasons for these observations are explained in Table 7.7.

Table 7.6 The comparison of results for different initial wind turbine MTTF when applying the hot standby redundancy model

Case study	**Initial wind turbine MTTF**			
	0.25	**0.5**	**0.75**	**1**
	Number of redundant converters needed for reduction in LPC of energy			
London Array	6	6	6	6
Kentish Flats	6	2	0	0
DOWEC	6	4	2	0

The observations on the summarised results in Table 7.6 indicate that the number of redundant converters required for the hot standby redundancy model to yield better economical results varies significantly between different offshore wind farm case studies and varying wind turbine reliability levels. This indicates that the solution proposed from Gamesa Eolica for the technical challenge of reduced reliability of the wind turbine converter system is only valid for specific wind turbine reliability levels and specific offshore wind farms, while a different hot standby redundancy model should be considered for different locations and wind turbine failure rates.

Table 7.7 The comparison of results for the percentage increase of wind turbine cost when applying the hot standby redundancy model

Case study	Number of redundant converters					
	1	2	3	4	5	6
	Percentage increase of wind turbine cost (%)					
London Array	-	0.85	1	1.2	1.4	1.6
Kentish Flats	-	2	2.5	3.1	3.7	4.5
DOWEC	-	0.5	0.8	1.1	1.38	1.68

Considering Table 7.7, the results obtained are divided into six sections for the six different wind turbine redundant systems that have been investigated in this Chapter. For each of the offshore wind farm case studies investigated, the percentage increase in the cost per installed wind turbine in the wind farm is reported. The cost of each wind turbine is calculated by dividing the CAPEX with the total number of wind turbines in the offshore wind farm case study, where the CAPEX is calculated by adding to the initial CAPEX, i.e. the CAPEX of the wind farm with no redundancy, with the cost of each added redundant converter for each wind turbine along with the costs incurred for a multi-phase generator and transformer, as compared to a conventional wind turbine system. It should be mentioned at this point that the costs associated with the increased size of wind turbine nacelle, as previously explained in paragraph 7.2.3 in this Chapter, are not considered since there is no published data to calculate them, however, there existence should be taken into consideration.

Considering the conclusions made from the results presented in Table 7.6, they can be explained by the significantly lower cost per installed wind turbine for the Kentish Flats offshore wind farm (3.4 million pounds), as compared to the London Array (11.2 million pounds) and DOWEC (7.3 million pounds) offshore wind farms. These wind turbine costs are directly related to the wind farm distance to shore and water depth that would greatly affect the CAPEX. When considering the results obtained from the hot standby redundant model for the Kentish Flats offshore wind farm in Table 7.7, the higher increased cost of each wind turbine results in higher increase of the CAPEX, which in turn would result in lower effect on the LPC of energy, as compared to the other offshore wind farm case studies, i.e. the London Array and DOWEC.

The results presented in Table 7.7 indicate that the increase in the cost of each installed wind turbine is a significant parameter when considering the application of a hot standby redundancy model on the converter system, since it greatly affects the CAPEX of the offshore wind farm and in turn the economical benefits of the hot standby redundancy model.

The results summarised in this paragraph have been obtained using the ‘PM 2’ scenario of the planned intervention maintenance policy, yet similar results could be obtained when using the ‘PM 1’ scenario. However, the effect of the hot standby redundancy model of the wind turbine converter system on the economics of offshore wind farms is expected to be higher for the ‘PM 1’ scenario, since the wind turbines would only be visited for repairs and maintenance once a year. This observation indicates that the offshore wind turbines would work for longer periods of time with no maintenance, as compared to the ‘PM 2’ scenario, which would inevitably result in the need for higher number of redundant converters.

7.8 Conclusions

A hot standby redundancy model on the wind turbine converter system has been investigated in this Chapter in order to examine how the model affects the economic viability of an offshore wind farm. Three different offshore wind farm case studies have been investigated, i.e. the London Array, the Kentish Flats and the DOWEC project.

The results obtained from applying the hot standby redundancy model using the planned intervention maintenance policy indicate that the number of redundant converters required to yield better economical results varies significantly between different offshore wind farm case studies and varying wind turbine reliability levels. It has also been concluded that the increase in the cost of each installed wind turbine is a significant parameter when considering the application of a hot standby redundancy model on the converter system, since it greatly affects the CAPEX of the offshore wind farm and in turn the economical benefits of the hot standby redundancy model.

Considering the investigation made in this chapter on the suitability of a redundancy model on different offshore wind farm case studies, it could be concluded that when assuming a wind turbine MTTF of $0.25 \leq MTTF \leq 1$ then the higherst level of power converter redundancy, i.e. 6 redundant converters, for the London Array offshore wind farm should be considered, this being a direct consequence of the high cost per wind turbine installed. On the other hand, considering the Kentish Flats offshore wind farm, a redundancy model would result in significant economical benefits for wind turbine $MTTF<0.5$ years, while for $MTTF>0.5$ years it should not be considered as a viable solutions and the conventional wind turbine system design with no power converter redundancy should be considered as a more economical solutions. The same observations could be made for the DOWEC offshore wind farm when assuming a wind turbine $MTTF>0.75$ years, since the redundancy model would not give any significant economical benefits, whilst for lower wind turbine MTTF the redundancy model should be considered since it could result in a decrease of the LPC of energy.

It can be concluded from the study on the redundancy of offshore wind turbines that the solution proposed for the technical challenge of reduced reliability of the wind turbine converter system is only valid for specific wind turbine reliability levels and specific offshore wind farm locations, while a different hot standby redundancy model should be considered for different locations and wind turbine failure rates.

8 Conclusions and Further Work

8.1 Conclusions

The aim of this work has been to evaluate the reliability, availability and maintenance of offshore wind farms. The operation in the marine environment has resulted in a reduction of offshore wind turbine reliability and accessibility and a significant increase in maintenance costs, as compared against equivalent onshore wind turbines. The maintenance of offshore wind farms is reported to be a challenging operation to tackle in order for the offshore wind farms to become competitive against other energy projects, as the O&M costs accounts for an average of 25% of the unit cost of energy produced.

The innovated contributions of this study have involved proposing solutions to the technical challenges identified for the reliability, availability and maintenance of offshore wind farms. The detailed models of planned intervention maintenance policy as a possible solution for the O&M practices of offshore wind farms have been established and computer simulation algorithms have been developed to simulate these models and compare the results obtained against the current O&M practices of reactive response. The CO2 emissions of offshore wind farms due to maintenance expeditions have been investigated through the development of computer based models for both the planned intervention and corrective maintenance strategy. Redundancy models have been investigated for the power converter system of an offshore wind turbine, as it has been identified as a critical component in terms of reliability, in order to examine possible benefits over the conventional wind turbine system.

The maintenance of offshore wind farms is an increasingly important area of research, particularly in the UK where there are several proposals for very large projects involving over 150 turbines, some of which are to be installed in locations with considerable distance offshore and in some cases in relatively deep water. Maintenance and repair of such installations accounts for an average of 25% of the unit cost of the energy produced, so it is important that the design of the equipment is as reliable as economic constraints can permit, and that the maintenance and repair strategies are as cost effective as they can be. It has been identified in this thesis that the complications are that there are a significant number of variables that influence the unit cost of energy, including:

- The unit design and manufacturing cost of the wind turbines (CAPEX)
- The installation costs
- The maintenance and repair costs
- The operations, logistics and support (ships and personnel) costs
- The reliability and availability of the wind turbines
- The capacity factor of the wind farm location
- The distance to shore
- The power rating of each wind turbine in the wind farm
- The accessibility and weather conditions

This degree of complication means that the evaluation of any strategic option is not straightforward and need careful assessment and acceptably accurate data, therefore the key question that is raised is:

"What sort of evaluation is needed to properly identify alternative maintenance and repair strategies and potential improvements in design to increase reliability?"

The answer is provided in the output from this Thesis in terms of a computer model with simulation algorithms, capable of calculating and evaluating strategic options, supported by data researched within this PhD thesis. The different steps and the significant conclusions reached in this thesis are summarised in the following paragraphs.

It is shown in the literature review of this thesis that the maintenance practices of offshore wind turbines is one of the most critical issues when considering the technical and economical viability of offshore wind farms. At present, the practises for maintenance of offshore wind turbines is reactive response, i.e. to undertake repairs at the first opportunity after a failure is detected, however this maintenance strategy is reported to result in ineffective and over-maintenance practices, leading inevitably to high cost per unit of energy produced. Although this current maintenance strategy has not yet been proven to be the optimum economic solution, it is the only practical one when taking into consideration the relative low number of wind turbines currently in operation, within an offshore wind farm located close to shore, whilst when considering the future offshore wind farms, which will be located far offshore, in nearly remote locations, with multiples of the power rating of current wind turbines then the reactive response is expected to become an unsuitable maintenance strategy and alternative solutions should be investigated. The evaluation of the existing maintenance and repair strategies for offshore wind farms lead to the following significant conclusions:

- Most current wind farm installations are quite small in number and relatively close to the shore.

- The operators have adopted a corrective maintenance strategy, where the wind turbines are repaired as soon as weather conditions and availability of specialised equipment permits.
- Current reliability levels of wind turbines are low as reported by a number of studies investigated in this thesis.
- The wind turbine structures are very tall and therefore lifting heavy components up to the height of the nacelle in heavy winds could become hazardous, i.e. the corrective maintenance strategy is heavily weather dependant.
- The wind levels, height of the waves and temperatures in winter months make it very difficult to undertake maintenance and repair actions, which lead to unplanned postponing, which negatively affects the LPC of energy.
- The specialised ships with stabilisers (legs) and special cranes are expensive to hire, while there are relatively few available.
- There is therefore limited track record on which to base future strategies for large and remote wind farms.

The research issue of great importance in this thesis was to propose and examine possible solutions to the identified technical challenges of maintenance of offshore wind farms. A planned intervention maintenance policy has been suggested as a possible substitution for the corrective maintenance strategy, in order to examine the effects oof the benefits of proactive maintenance practices that a planned invervention could offer.

An O&M model for the proposed solution of planned intervention maintenance policy for offshore wind farms is developed and simulated to investigate possible technical and financial benefits when compared against the current maintenance practices. It is identified that there is a range of different models available that simulate the current maintenance practices of offshore wind farms, however these models have constraints and limitations, e.g. lack of stochastic behaviour for a number of different input parameters; the lack of the effect of marine environment on wind turbine reliability and accessibility; and incomplete economical factors, which limit the ability to examine all the different parameters that affect offshore wind farms. In additions, the suitability and applicability of the existing models for the current O&M practices is reported to be inadequate for the planned intervention maintenance policy, therefore novel models are developed in this thesis, i.e. reliability, economic, energy and stochastic models, in order to address the limitations and constraints of existing models and help to accurately simulate a planned intervention maintenance policy.

Two different methods are used in this thesis to design the planned intervention maintenance policy and to analyse key performance parameters affecting the maintenance of offshore wind farms. The Life Cycle Cost Analysis (LCCA) technique is used to analyse the costs of developing an offshore wind farm and how these costs are interrelated, while the Structured Analysis and Design Technique (SADT) is employed to investigate the key offshore wind farm parameters affecting a planned intervention maintenance policy.

The O&M model for the planned intervention maintenance policy requires the development of sub-models that interact with each other to simulate all the aspects of the maintenance practices of offshore wind farms, i.e. a reliability model, an energy model, an economic model and a stochastic model. These models interact with each other having a bidirectional relationship with the stochastic model, in order to produce results in terms of wind farm availability, cumulative energy output, levelised production cost of energy CO_2 emissions, etc.

Considering the lack of published data for failure rates for offshore wind turbines, then a reliability model is developed to calculate accurate ranges of offshore wind turbine failure rates using empirical stress factors on hard data obtained from onshore wind turbine databases, since it has been identified that the marine environment has greatly affected the reliability of offshore wind turbine components. The calculated results of the reliability model showed that the failure rates of offshore wind turbines are significantly higher, as compared against onshore wind turbines, and are calculated to have an MTTF of $0.25 \leq MTTF \leq 1$ in years.

An economic model is developed to simulate the maintenance costs of offshore wind farms when considering the significant parameters that affect the economics of offshore wind farms, e.g. interest rates, cost of repairs, cost of preventive maintenance and costs of maintenance expeditions. The economic model uses an established method, the levelised production cost of energy, for calculating the costs associated with installing, operating and decommissioning wind farms, while it has been modified in this thesis to consider all the unique economic parameters of offshore wind farms, e.g. cost of vessel hiring, as compared against onshore wind farms. This method has been extensively used for the financial comparison between different wind farm projects and in general different power projects. The outputs of this model in terms of cost of unit of energy produced are used in this thesis to assess and compare different maintenance scenarios.

An energy model is developed to calculate the cumulative energy produced from the offshore wind farm when considering energy losses due to failures, repairs and downtime. The energy model uses interpolation methods to calculate the energy generated from every wind turbine between scheduled maintenance visits by knowing the exact time the wind turbine failed.

A stochastic model is developed that uses the Monte Carlo method to simulate the variability and stochastic behaviour of different input parameters, e.g. time to failure of wind turbines, whilst a deterministic approach to these parameters would not give accurate output results, since the O&M model would have to be constrained to fixed input values. The stochastic model interacts with the other models in a bidirectional relationship to generate the statistical output results of the O&M model, e.g. likely wind farm availability.

Two different planned intervention maintenance strategies have been investigated in this thesis, i.e. ‘PM1’ and ‘PM2’, which simulate one or two planned maintenance periods during an operational year for all the offshore wind turbines. The O&M models developed for the planned intervention maintenance policy scenarios have been validated against hard data from studies that simulate the current maintenance practices for large offshore wind farms. The validation process indicates that the results obtained from the developed models are directly comparable with the hard data showing a consistency for the different case studies that were simulated. The verification of the developed models has been conducted by establishing a baseline offshore wind farm to perform a sensitivity analysis on the developed O&M model to give added confidence on the output results. The input parameters of the baseline offshore wind farm have been varied to assess how the O&M model reacts and has been shown that the results obtained follow the background theory and the equations developed in the different sub-models.

Different offshore wind farm case studies have been considered in this thesis to simulate the planned intervention maintenance policy scenarios and produce results in terms of wind farm availability, cumulative energy output, levelised production of energy and CO2 emissions due to maintenance expeditions. For each of the case studies, investigations were carried out to determine the benefits and drawbacks of the planned intervention maintenance policy with variations in the key input parameters of the offshore wind farm over a range of input variables. This thesis has evaluated the unit cost of energy for the two planned intervention maintenance policy scenarios based on regular and carefully planned maintenance and repair practices, undertaken either once a year (in summer – PM1) or twice a year (typically in May and October – PM2). The significant conclusions reached from the output results of the simulations are:

- The planned intervention maintenance policy scenarios (either PM1 or PM2) may not be economic for existing offshore wind farms which are located close to shore and consist of a small number of wind turbines.
- For much larger and more remote offshore wind farms the planned intervention maintenance policy can be justified particularly if the wind turbine MTTF is significantly higher than current levels:
    - Considering wind turbine MTTF below 0.25 years, then the corrective maintenance strategy would yiled better results.

  - Considering wind turbine MTTF of 0.25>MTTF<0.35, then the PM1 scenario may be the more economic, as compared against PM2.
  - Considering wind turbine MTTF larger than 0.35 years, then the PM2 scenario is generally more economic, as compared against PM1.
- However the actual results of the simulation are dependent on the unit reliability (MTTF), manufacturing and installation costs, which are generally very high if the installation is in deep water and/or a long distance from shore.

More specifically, the investigations on the planned intervention maintenance policy for the different offshore wind farm case studies appear to indicate that the decision on the preferred maintenance scenario, i.e. ‘PM 1’ or ‘PM 2’, depends upon the key input parameters, e.g. the reliability of the wind turbines, the wind turbine repair time, the capacity factor of the wind farm, the maintenance transportation cost, the energy output and the LPC of energy. For wind turbine reliability levels of MTTF>0.35 the ‘PM 1’ scenario is preferred as it would yield LPC of energy lower, as compared to the ‘PM 2’ scenario, whilst for wind turbine MTTF higher than 0.35 years then the ‘PM 2’ scenario would be preferred. This observation indicates that there is a specific wind turbine reliability level, i.e. MTTF=0.35, upon which the decision on the planned intervention maintenance policy scenario could be based.

The variation in the wind turbine mttr and mtpm could result by the change in wind turbine accessibility levels, due to weather and sea state, or availability of transportation means or availability of spare parts. By varying the wind turbine mttr and mtpm for the different offshore wind farm case studies the results indicate the significance of energy losses during the scheduled maintenance visits. A significant conclusion reached from the results obtained from the simulations is that as the repair time of the wind turbines increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the ‘PM 2’ scenario. The same conclusions could be reached when varying the maintenance transportation costs, which could result by the change in the availability of maintenance vessels. The results also indicate that as the hiring cost of maintenance vessels increases then the ‘PM 1’ scenario yields lower LPC of energy for a larger wind turbine MTTF range, and consequently would be preferred over the ‘PM 2’ scenario.

The change in the capacity factor of the offshore wind farm could indicate a change in the location or the wind levels of the location. The interesting point to observe from the results of the comparison between the two planned intervention maintenance policy scenarios indicate that as the capacity factor increases the ‘PM 2’ scenario would be preferred over the ‘PM 1’ scenario as it achieves lower LPC of energy.

Further, a significant conclusion reached when comparing the results between the planned intervention maintenance policy scenarios for the energy output, is that for low wind turbine reliability levels, i.e. $0.25 \leq MTTF \leq 0.35$, the ‘PM 1’ scenario yields higher energy output, as compared to the ‘PM 2’ scenario, this being explained by the effect of the period selected for the wind farm maintenance expeditions to take place, when considering the energy losses during the scheduled maintenance visits in relation to low reliability levels.

Considering the ‘PM 1’ scenario, the scheduled maintenance visits are planned during July, where the energy losses for repairs and preventive maintenance would account for a maximum of 5.8% of the total energy output over the operational year, whilst considering the ‘PM 2’ scenario, the scheduled maintenance visits are planned twice a year, during October and May, where the energy losses for repairs and preventive maintenance would account for a maximum of 15.9% (8.8% for October and 7.1% for May) of the total energy output for the operational year. The results obtained indicate that as the wind turbine MTTF decreases then more wind turbines will fail during the year, so the cumulative repair time for all the wind turbines in the offshore wind farm increases, which in turn results in higher energy losses for the ‘PM 2’ scenario, as compared to the ‘PM 1’ scenario. It should also be considered that the proactive nature of the planned intervention maintenance policy would require preventive maintenance tasks to take place on all the wind turbines, which in turn results in the wind turbines to stop operation for the maintenance work to take place.

This practice, which has been identified as a main disadvantage of planned intervention maintenance policy, is performed twice as many times for the 'PM 2' scenario as compared to 'PM 1', which in turn results in higher energy loss.

However, when considering higher wind turbine reliability levels, i.e. 0.35≤MTTF≤1, then the 'PM 2' scenario achieves significantly higher energy output, regardless of the case study investigated, as compared to the 'PM 1' scenario, this being explained by the lower number of failures resulting in lower energy losses during the scheduled maintenance visits. A significant conclusion reached from the comparison of the energy output results between the different case studies investigated is that as the number of wind turbines in a wind farm decreases then the energy output also decreases, which in turn affects significantly the cost of energy produced.

The results obtained from the investigations on the percentage of maintenance costs in the LPC of energy have shown that the 'PM 2' scenario yields significantly higher results across the range of wind turbine MTTF, as compared to the 'PM 1' scenario, but the LPC of energy for the 'PM 2' scenario is lower as compared to the 'PM 1' scenario for wind turbine MTTF>0.35. This indicates that despite the higher maintenance costs observed for the 'PM 2' scenario, the higher energy output that is achieved, as it benefits from higher wind farm availability, results in lower LPC of energy and shows that the 'PM 2' scenario would be preferred over the 'PM 1' scenario for wind turbine MTTF>0.35. On the other hand, for wind turbine MTTF range of 0.25≤MTTF≤0.35 the 'PM 1' scenario would be preferred, since it achieves higher energy output and lower LPC of energy, as compared to the 'PM 2' scenario, which suffers from higher energy loss due to the planned intervention maintenance policy nature.

The results obtained for each offshore wind farm case study investigated in this thesis in terms of cost of unit of energy produced were compared against hard data from different studies, in order to assess the suitability and applicability of the planned intervention maintenance policy over the current maintenance practices. The significant conclusions reached from the comparison of the results indicate that the planned intervention maintenance policy may not be a suitable economic alternative for the O&M strategy for prototype and small offshore wind farms located close to shore and consisted of a small number of wind turbines. However, when considering future offshore wind farms with large number of wind turbines located far offshore, then the planned intervention maintenance policy could potentially produce results that are significantly better, as compared against the corrective maintenance strategy, in terms of economical viability, i.e. the results show a significant reduction in LPC of energy. When considering future very large offshore wind farms, the employment of planned intervention maintenance policy has the potential to yield a considerably reduced LPC of energy as compared against the current maintenance practices, while the results are found to be directly comparable, and in some cases even lower, to equivalent onshore wind farms.

More specifically, a significant point of interest has been the comparition of the simulated results of the wind farm availability obtained from the planned intervention maintenance policy, against the published results for the corrective maintenance strategy. Considering the accessibility level of existing offshore wind farm, when employing the corrective maintenance strategy, then the wind farm availability achieved is 75-80%, whilst for the planned intervention maintenance policy is simulated to be 46-56% for the 'PM 1' scenario and 65-70% for the 'PM 2' scenario. These results indicate that the corrective maintenance strategy achieves higher wind farm availability, this being a result of the nature of the planned intervention maintenance policy which aims to compromise wind turbine availability levels, by simulating less maintenance expeditions in an attempt to achieve a more competitive price of energy produced.

The results obtained for the percentage of maintenance cost in the CAPEX versus wind turbine MTTF, they have been used for comparing the planned intervention maintenance policy between the different case studies investigated in order to identify the key parameters that affect the economics of the projects. When comparing the percentage of maintenance cost in the CAPEX with the results obtained from the London Array offshore wind farm, it can be concluded that the percentage of maintenance cost in the CAPEX for the Kentish Flats offshore wind farm is found to be significantly higher, which can be explained by the fact that the cost of each installed wind turbine, i.e. CAPEX divided by the total number of wind turbines in the wind farm, for the London Array is calculated to be 11.2 million pounds per wind turbine and for the Kentish Flats is calculated to be 3.5 million pounds per wind turbine. This indicates that the CAPEX of the Kentish Flats offshore wind farm is significantly lower, as compared to the London Array.

Considering the comparison of the LPC of energy between the London Array and the Kentish Flats offshore wind farms, where the results indicate that the Kentish Flats achieves lower LPC of energy, this being a direct result of the difference in the CAPEX of each project. The Kentish Flats is an offshore wind farm located closer to shore (25 km) and at shallower waters, which decreases the cost of wind turbine foundations, cables, and installation process, which account for around 40% of the CAPEX, as compared to the London Array offshore wind farm. This conclusion could also be reached by dividing the CAPEX of each case study with the total number of wind turbines in the wind farm to calculate the cost per installed wind turbine. For the Beatrice offshore wind farm it is calculated to be 17.5 million pounds per wind turbine installed, for the London Array offshore wind farm is calculated to be 11.2 million pounds and for the Kentish Flats is 3.5 million pounds per wind turbine installed. These results point out the significant effect of the distance to shore and the water depth on the LPC of energy of offshore wind farms.

The comparison of the results from the Kentish Flats case study against the results obtained from the DOWEC project indicate that the DOWEC project yields significantly lower LPC of energy, despite the fact that it has a considerably higher calculated cost per installed wind turbine, i.e. 5.84 million pounds. This could be explained by the fact that the DOWEC project achieves significantly higher energy output, as compared to the Kentish Flats, since each wind turbine has twice the power rating of those installed in the Kentish Flats. The significant conclusion reached from the observation of these results is that the wind turbine power rating has a higher effect on the LPC of energy than the distance to shore and the water depth.

The significant conclusion reached from these results is the great potential to produce lower LPC of energy at competitive levels for future large offshore wind farms, should the reactive response be substituted by the planned intervention maintenance policy. Considering the findings of the investigations in this area of research then it is the author's view that as the number of offshore wind turbines within a wind farm and their distance to shore and water depth increase then a planned intervention maintenance policy should be considered as a viable solution.

The investigations from the simulations of the CO_2 emissions for offshore wind farms indicate that the levels of CO_2 emissions are not negligible, as has been falsely believed in literature, while different wind farm design parameters need to be considered when developing future offshore wind farms to mitigate the risks of producing high levels of CO_2 emissions, i.e. the distance to shore, the wind turbine reliability and the maintenance practices adopted play a significant role in minimising the CO_2 emissions for offshore wind farms. The significant conclusions reached in this thesis from the investigations in the CO_2 emissions for offshore wind farms are listed below:

- The output results from the simulations show a significant difference between the reactive response and planned intervention maintenance strategies, which is explained by the significantly higher number of maintenance expeditions for the corrective maintenance strategy which in turn result in higher CO_2 emissions per kWh produced.
- The planned intervention maintenance policy could achieve a reduction of an average of 70% in the CO_2 emissions, as compared against the corrective maintenance strategy.

- The planned intervention maintenance policy could achieve a reduction of an average of 80% in the ratio of CO_2 emissions to the energy output, as compared against the corrective maintenance strategy.
- Considering a future offshore wind farm, e.g. the Opti-Owecs project, then the total ratio of CO_2 emissions to the energy output could reach up to 41.5 grams of CO_2 per kWh produced by employing the corrective maintenance strategy, whilst if the planned intervention maintenance policy would be employed then only 21.8 grams of CO_2 per kWh would be produced.

The investigation conducted on the reliability of offshore wind turbines has lead to the conclusion that the wind turbine electrical system is a critical component in terms of failure rates. It has been identified that 22% on average of the total wind turbine failure rate is claimed on the power converter system and power converter related failures. Therefore, this thesis has set out an investigation to address this technical challenge by examining a hot standby redundancy model for the converter system of the offshore wind turbine. This thesis has used the modelling and simulations to evaluate the economics of improving the reliability of the power converter system by providing between 2 and 6 redundant power converters rather than only one, which, if they fail, reduce the power output in proportion to the number of operating converters divided by the number of installed power converters, e.g. for 6 installed power converters, if one fails, the output power drops to 5/6 of the initial power output. This redundancy model on the power converter system is simulated in order to examine how the model affects the economic viability of an offshore wind farm, where the output results from three offshore wind farm case studies have been examined, i.e. the London Array, the Kentish Flats and the DOWEC project.

The results obtained when employing the hot standby redundancy model using the planned intervention maintenance policy indicate that the number of redundant power converters required to yield better economical results varies significantly between different offshore wind farm case studies and varying wind turbine reliability levels. It is also concluded that the increase in the cost of each installed wind turbine is a significant parameter when considering the application of a hot standby redundancy model on the power converter system, since it could significantly affect the economical viability of the offshore wind farm. It is shown from the simulated results that the solution proposed from Gamesa Eolica using 6 parallel power converters is only valid for specific wind turbine reliability levels and specific offshore wind farm locations, whilst a different hot standby redundancy model should be considered for different locations and wind turbine failure rates. The significant conclusion reached from these investigations is that the distance to shore, the water depth and the cost of each installed wind turbine are the key parameters that largely affect the redundancy model of the offshore wind turbine converter system and would therefore define how the hot standby redundancy model should be more effectively deployed.

Considering the investigation on the suitability of a redundancy model on different offshore wind farm case studies, it has been concluded that when assuming a wind turbine MTTF of 0.25≤MTTF≤1 then the higherst level of power converter redundancy, i.e. 6 redundant converters, for the London Array offshore wind farm should be considered, this being a direct consequence of the high cost per wind turbine installed. On the other hand, considering the Kentish Flats offshore wind farm, a redundancy model would result in significant economical benefits for wind turbine MTTF<0.5 years, while for MTTF>0.5 years it should not be considered as a viable solutions and the conventional wind turbine system design with no power converter redundancy should be considered as a more economical solutions. The same observations could be made for the DOWEC offshore wind farm when assuming a wind turbine MTTF>0.75 years, since the redundancy model would not give any significant economical benefits, whilst for lower wind turbine MTTF the redundancy model should be considered since it could result in a decrease of the LPC of energy.

It can be concluded from the study on the redundancy of offshore wind turbines that the solution proposed for the technical challenge of reduced reliability of the wind turbine converter system is only valid for specific wind turbine reliability levels and specific offshore wind farm locations, while a different hot standby redundancy model should be considered for different locations and wind turbine failure rates.

The research carried out in this thesis has given eveidence with the main contribution being the knowledge that the reliability, availability and maintenance of offshore wind farms need to be carefully assessed by considering the effects of the weather related accessibility (i.e. wind and wave conditions), the stochastic behaviour of offshore wind turbine failure rates, the distance to shore, the LPC of energy, the CO2 emissions due to maintenance expeditions and wind turbine reliability optimisation, which would define the most suitable and effective maintenance strategy for offshore wind farms to secure economically viable projects.

8.2 Further work

The models already developed in this thesis could easily be extended or modified to look at further cases of maintenance strategies for offshore wind farms. As illustrated in Chapter 6 if different locations and weather accessibility impinge for the offshore wind farms then other maintenance strategies could potentially yield more competitive price of unit of energy produced.

The O&M models developed in this thesis could also be extended or modified to investigate the employment of planned intervention maintenance policy for other offshore renewable energy projects. Emerging technologies such as wave turbines, semi submersible wind and wave devices, marine current turbines etc, could become possible candidates for the application of planned intervention maintenance policy, which can be an intriguing area for further research.

The redundancy technique that is investigated in this thesis is focused on the wind turbine power converter system, however other wind turbine components, e.g. power electronics and blades, also suffer from high statistical failure rates. A further examination of the hot standby redundancy technique developed in this thesis to examine possible solutions for other low reliability wind turbine components is an interesting area for further research.

This thesis investigated a hot standby redundancy technique for the wind turbine converter system; however other redundancy techniques, e.g. cold and warm standby, could be further investigated to assess their benefits and disadvantages for the identified technical challenge of reduced offshore wind turbine reliability. Different technical and economical solutions could result from these redundancy techniques that are interesting to investigate.

An interesting area that could be further explored is the employment of leasing different components for the offshore wind farm industry. Leasing is a process by which a firm can obtain the use of certain assets for which it must pay a series of contractual, periodic payments. Generally the leaser, i.e. the company that performs the leasing practice, is either the manufacturer or an independent leasing company, while the lessee is the operator of the equipment. The leaser buys the equipment from the manufacturer and is responsible to undertake the repairs of any faulty equipment, while the lessee is responsible for routine preventive maintenance. The leasing principle can be seen in many industries, e.g. commercial and military support airplanes and engines, trains, and trucks. This practice could be applied to wind turbine components, i.e. generator, gearboxes and blades which in turn could reduce the risks involved with maintenance and repair costs and could potentially result in a reduction of the cost of energy produced.

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Appendices

A. Wind Turbine Power Output

The energy extracted from the wind is produced by the aerodynamic force lifting the wind turbine blades. The wind energy is converted to mechanical energy, and then by the use of a generator is transformed to electrical energy.[99]

When considering a horizontal axis wind turbine, from the continuity equation of fluid mechanics the mass flow rate of air dm/dt through a rotor disk swept area A, as seen in Figure A.1, is given by equation A.1 below:[120]

$$\frac{dm}{dt} = \rho A U \qquad \text{A.1}$$

Where, U is the velocity (if assumed to be constant) of the air going through the rotor swept area A, and ρ is the density of the air, if assumed constant.

The general expression for wind power is given by equation A.2 below:[1,53]

$$P_{wind} = \frac{1}{2}\frac{dm}{dt}U^2 \qquad \text{A.2}$$

and by using Eq A.1 $\Leftrightarrow$ $P_{wind} = \frac{1}{2}\rho A U^3$ A.3

Equation A.3 shows that the power of the wind is proportional to the swept area of the wind turbine rotor, or proportional to the blade diameter squared. However, more importantly the power is proportional to the third power of the wind speed, with the value of density remaining constant.

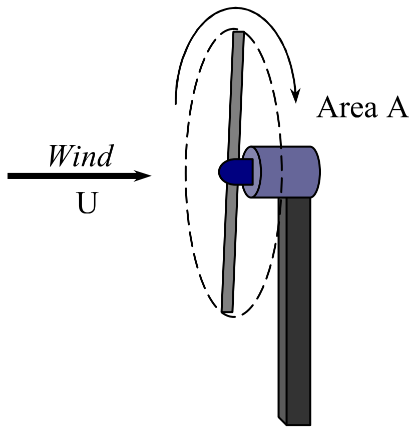


Figure A.1 Power from the wind on a horizontal axis wind turbine

Naturally, wind speed in the atmosphere is not constant, but varies greatly over time, and this is expressed mathematically as U = U (t).[120] According to this variability of the wind and in order to accurately calculate the energy produced by a wind turbine then, statistical techniques have to be used.[120,108] To comprehend how a wind turbine produces energy some important parameters are explained in the following paragraphs. The first one is the tip speed ratio λ_{tip}, which is simply the rate at which the end of the blades of the wind turbine turn in comparison to how fast the wind is blowing and is given by:[53]

$$\lambda_{tip} = \frac{Blade\,speed}{Wind\,speed} = \frac{\omega R}{U} \qquad \text{A.4}$$

Where ω is the angular velocity of the wind turbine rotor and R is its radius.

In the case of a very slow rotational speed, wind will pass unperturbed through the gaps between the blades, with minimum movement of the rotor and therefore it will be inefficient.[120] On the other hand, a very high rotational speed will make the rotor appear solid to the wind, the air will become turbulent and again limited movement will make the rotor inefficient. At this point the importance of parameter λ_{tip} can be understood, as at some value between very slow and very fast wind speeds lies the optimum rotational speed for transmitting power to the rotor.[1,120]

Another important parameter that is analysed is the rotor power coefficient, C_p, given by:[53]

$$C_p = \frac{Rotor\ power}{Power\ in\ the\ wind} = \frac{P_{100}}{\frac{1}{2}\rho A U^3} \qquad \text{A.5}$$

Where, P_{100} is the power at 100% machine efficiency.

The C_p coefficient is in other words the fraction of the energy in the wind that is extracted by the rotor. From the conservation of energy applied to the blades, it is obvious that the wind leaving the blades has kinetic energy and hence the extraction of energy from the wind can not be 100%. The Betz's linear momentum theory gives a maximum fractional energy extraction of 59.26%.[108] This maximum limit is not caused by any deficiency in the designing of the wind turbine but because the air leaving the wind turbine blades has a velocity.[108]

The air that passes through the rotor cannot slow down because it needs to stay out of the way of the air behind it. So at the rotor, the energy is extracted by a pressure drop. The air directly behind the wind turbine is at sub-atmospheric pressure, while the air in front has a pressure greater than the atmospheric.[53,108] It is this high pressure in front of the wind turbine that deflects some of the upstream air around the turbine. This causes the air passing through the rotor plane to have a smaller velocity than the free stream velocity. The degree at which air at the wind turbine is less than the air far away from it is called the axial induction factor. Betz was able to develop an expression for *Cp* in terms of the induction factors.[53,108] This is done by the velocity relations being substituted into power and power is substituted into the coefficient of power definition.[53,108] The relationship Betz developed is given below:

$$C_p = 4a\,(1\text{-}a)^2,$$

where, a is the axial induction factor.

After explaining the important mathematical parameters that govern the wind energy generation, the overall efficiency of a wind turbine is shown that is calculated by:[53,108]

$$\eta_{overall} = \frac{P_{out}}{\frac{1}{2}\rho A U^3} = \eta_{mech} * \eta_{elec} * C_p \qquad \text{A.6}$$

And rearranging to get the total Power output:

$$P_{out} = \frac{1}{2}\rho A U^3 \left(\eta_{mech} * \eta_{elec} * C_p\right) \qquad \text{A.7}$$

Where η_{mech} is the efficiency of the mechanical components of the wind turbine and η_{elec} is the efficiency of the electrical and electronic components.

B.1 Wind Turbine System Components

It is interesting that over 98% of the wind turbines that exist in the world are of the upwind horizontal axis type (HAWT), as shown in Figure B.1.[1,108] It is worth mentioning that there have been numerous designs on wind turbines as an alternative to the horizontal axis design. The best proposition that was also built in many sites is the vertical axis wind turbine, (VAWT) as shown in Figure B.1. However, none of those designs could compete with the HAWT in terms of economics in combination with efficiency in energy output.[120] Furthermore some other designs that never managed to succeed after the prototyping stage are the cross-wind Savonius, only used in some hydro-projects; the cross wind paddles and the unconfined vortex design.[120]

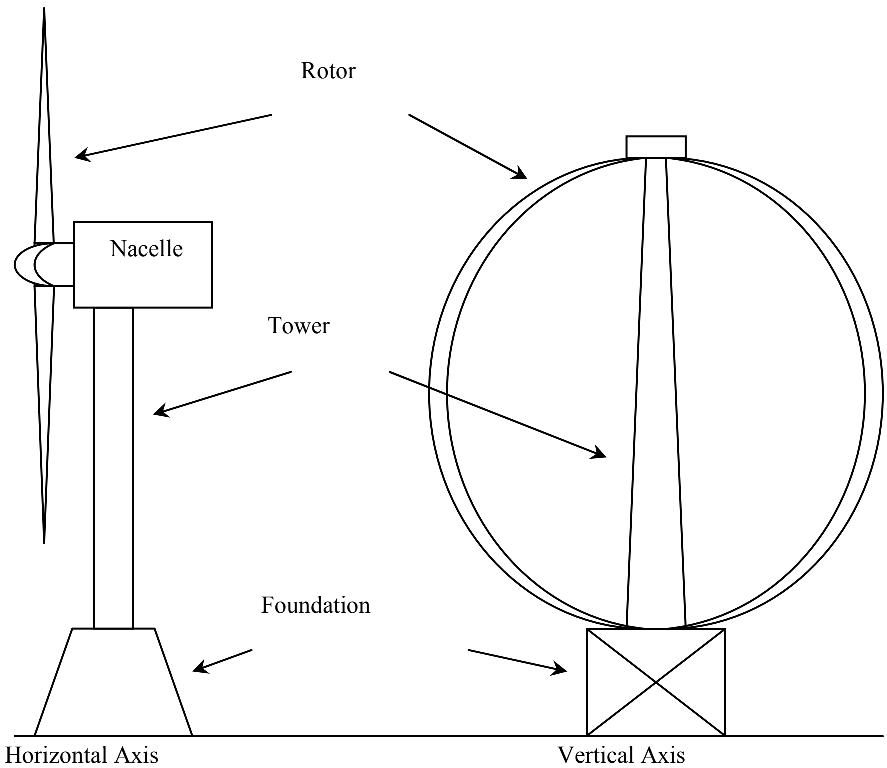
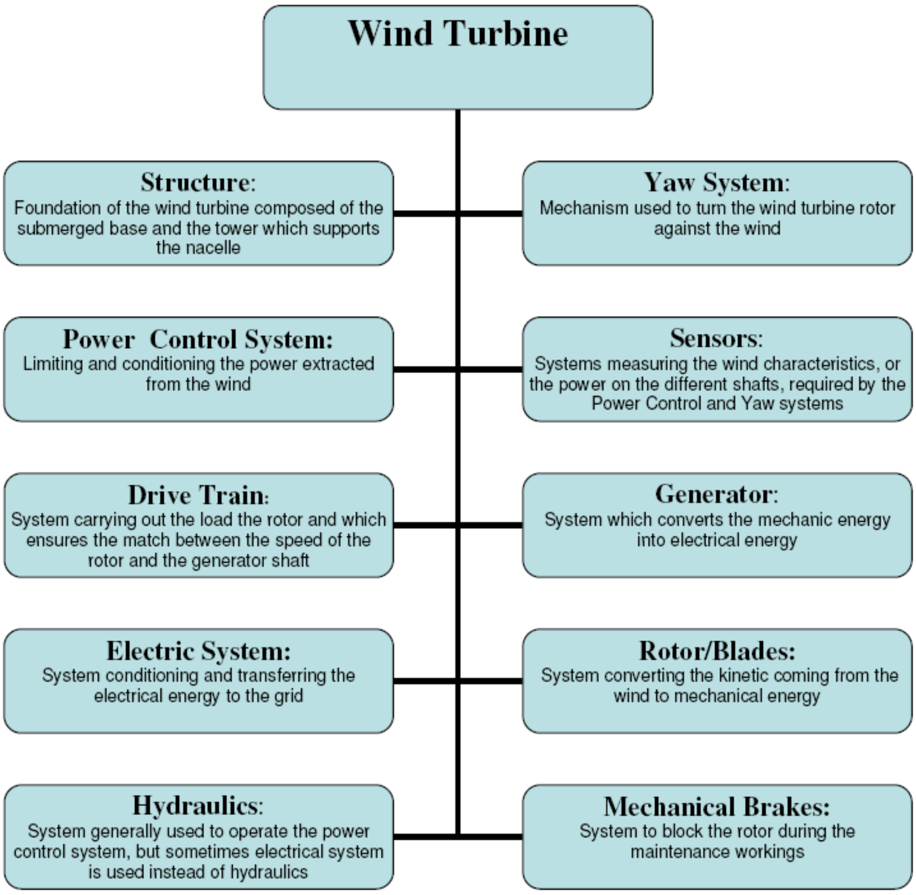


Figure B.1 The structural difference between horizontal and vertical axis wind turbines



Blades	Fibreglass or carbon fibre reinforced plastics. Stall regulated blades limit lift, or momentum, when wind speeds are too great to avoid damaging the machine. Variable pitch blades rotate to minimise their surface area and thereby regulate their rotational speed
Gearbox	Converts low speed rotation from the input shaft of the rotor to high speed rotation, which drives the generator shaft. Large modern machines use planetary gear boxes
Generator	Converts the mechanical energy to electrical. A number of different types are used between synchronous, induction generators but also permanent magnet ones
Power Electronics	Couples the generator output to the step-up transformer input, typically with an electrical (IGBT) bridge, allowing the generator to run at variable speed while still outputting 50 or 60 Hz AC to the grid

Figure B.2 The key components of a typical wind turbine.[41]

The key components of a wind turbine are explained and recent technological innovation are analysed in the following paragraphs with focus on reliability and maintainability issues. As seen in Figure B.1, the nacelle is in simple terms a “container box”, mounted on the tower. This “box” houses all the components needed to generate electricity from the wind. This usually includes the gearbox (if present), the generator, the control and electronics systems, the bearings, the shafts, and all the components of the transmission system, as observed in Figure B.2.

B.1.1 The rotor

The rotor, of a wind turbine consists of two parts, the hub and the blades. Early designs of large wind turbines had a fixed-speed operation, meaning that the rotor produced energy while working at constant speed.[120] For instance the rotor of a wind turbine of 700 kW power rating has a rotating speed of about 20 to 25 rpm.[99] This means that the maximum coefficient of efficiency (C_p) is only available for that particular wind speed range and for all other wind speeds the efficiency is very low. That is the reason why most of the modern wind turbines have a variable speed or two-speed operation. This means that the rotor speed and wind speed are matched in order for the rotor to maintain the best geometry for maximum efficiency.

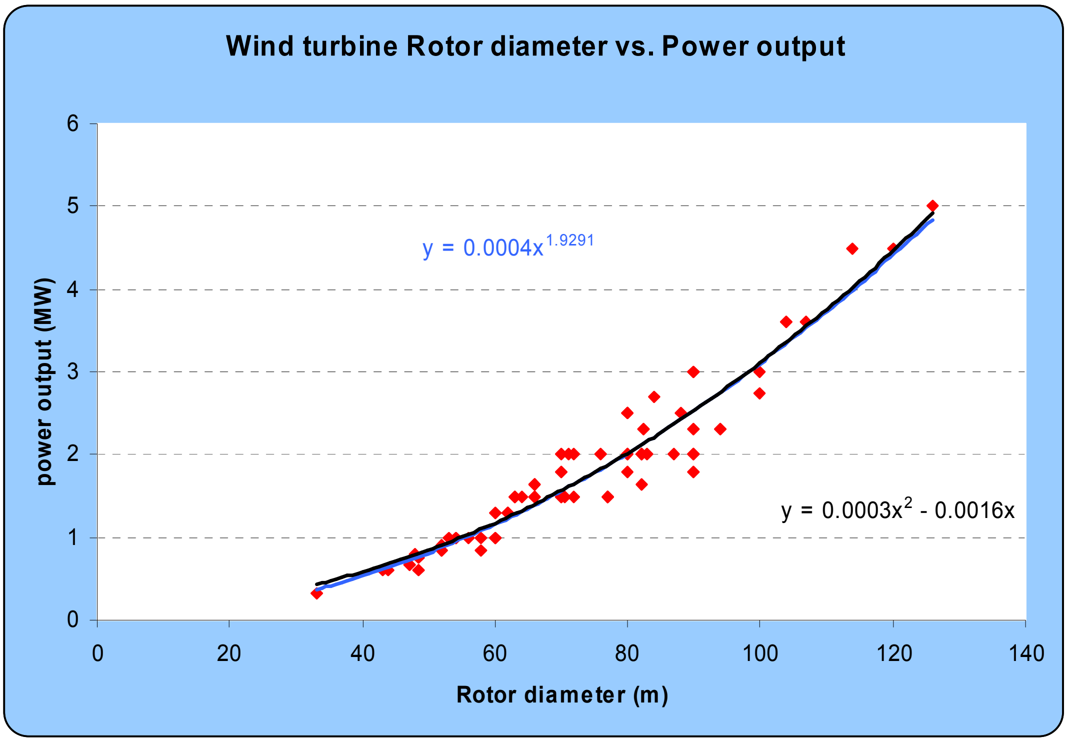


Figure B.3 The relationship between rotor diameter and power output.[121]

An important difference between variable speed operation and conventional fixed speed wind turbines is that moderate speed variations are still permitted.[98] This reduces loads on the drive train and reduces the amount of pitch activity required for power regulation. Furthermore, with the use of variable-speed wind generators, energy can also be produced in low wind speeds, where the noise levels are minimised.[8]

Figure B.3 shows the relationship between the power output and the rotor diameter of the majority of the commercial wind turbines, as would be expected from the equations presented in Appendix A. It can be seen that the rated power output increases at about a square by using the values available for the most commercial wind turbines in industry.

B.1.2 Power Control System

The necessity to control aerodynamic forces on the wind turbine rotor, to maximise efficiency and protect the wind turbine in extreme weather conditions, has forced the industry to equip all wind turbines with different types of power control systems. Three types of these systems can be found, and are explained below:[41,108,120,122]

- **Pitch Control.** The basic concept of 'active' pitch controlling is based on the ability to turn the rotor blades around their longitudinal axis.[41,108,120,122] Generally, this has two purposes on a wind turbine; firstly by adjusting blade pitch angle, power and speed control of the rotor can be achieved and secondly, an aerodynamically braking system can be used.[41] The basic type of blade pitch control used was hydraulic driven, however the last few years electronically controlled pitch motors of very compact design are used on electrical blade pitch drives.[123] Besides, the advantages this method has for optimum power controlling, it introduces concerns regarding high power fluctuations at high wind speeds and reliability problems due to the excessive complexity.[123]

- **Stall Control.** This concept of controlling the blades is less complex as compared to the pitch control. The blades are bolted onto the hub at a fixed angle and the design of the rotor aerodynamics causes the rotor to stall when the wind speed exceeds a certain level.[123] By using the passive control option, and with the absence of hydraulic or electrical drives, electronic power and speed control arrangements, shows considerable simplification and in turn a more reliable design.[41,108,120,122] However, problems arise for large wind turbines at the process of start-up or emergency shut-down.[41,108,120]

- **Active Stall Control**. With this concept the stall of the blades is actively controlled by pitching the blades.[41] The basic concepts of operation for this type of control are; at low wind speeds the blades are pitched similarly to a pitch controlled wind turbine, achieving higher efficiency levels, and at high speeds the blades go into a deeper stall by being pitched slightly into the direction opposite to that of a pitch controlled turbine.[2] This concept of power control not only provides higher efficiency at lower wind speeds from the stall control, but also makes it easier to start up the wind turbine and to carry out emergency stops, e.g. for maintenance.[41]

A comparison of all three concepts of power control is given in Figure B.4, where the power curves are represented.[124] It can be observed that both active stall and pitch control can limit the power smoothly by adjusting the blades, however when stall control is used a small overshoot appears.

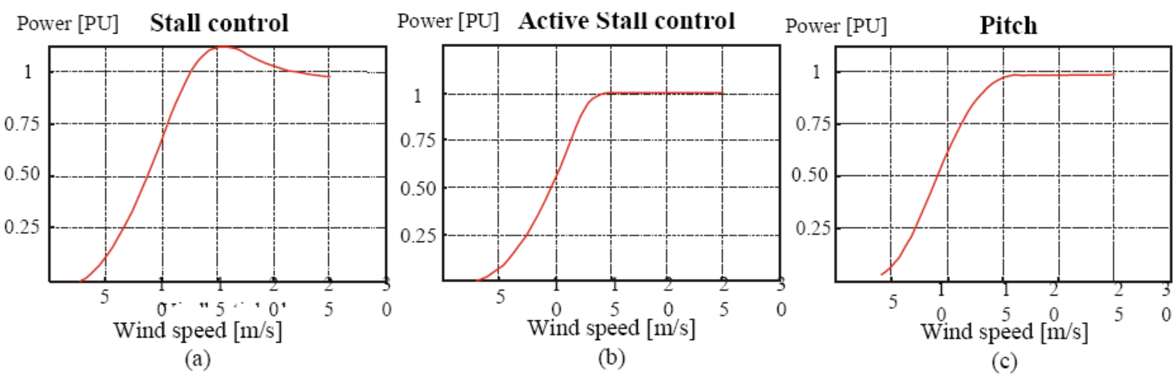


Figure B.4 Power characteristics of fixed speed wind turbines.[124]

In a condition of low wind speeds the pitch-controlled wind turbines are in favour, as the rotor blades can be kept at a constant optimum angle for maximum power output.[1,108] On the other hand at very strong wind speeds, stall-regulated wind turbines have advantage, as the wind oscillations, when the stall effect becomes effective, can be converted into power oscillations that are smaller than those of the pitch-controlled turbines in a corresponding regulated mode.[108,122] The stall regulated design remains viable and competitive nowadays, but variable speed technology, associated with pitch control, are preferred by the manufacturers.[61,62]

B.1.3 The Blades

The blades on the majority of the modern turbines nowadays are manufactured from composite materials, mainly fibreglass or carbon fibre reinforced plastics, (GRP or CFRP).[61,62] Despite carbon's large cost, most of the blade manufacturers have invested in the development of carbon technology, because of light weight design and improved strength.

The designing of the blades is one of the most difficult parts when designing a wind turbine. As the blades are made from composite materials, they share a difficult design detail at the root where the bending moments are greater and the change of stiffness between the blade materials to the steel hub leads inevitably to stress concentrations.[53] However a well chosen airfoil should have a number of characteristics, as listed below:

- High lift to drag for efficiency over a wide range,
- Good stall characteristics,
- Insensitivity to roughness and
- Low noise production.

Nowadays, new methods of improving the wind turbine power output by redesigning the blades have been revised, one of them is the use of vortex generators.[30] These small fins, which are placed at the boundary layer of the blade, can give a 4 to 6% rise in the power output of the machine.[108] Other blade performance tuning gadgets are the stall strips; fences and Gurney flaps.[108]

An issue has been raised over the last 15 years for the number of blades that a wind turbine should have. A number of studies on aero-elasticity, blade-hub interaction, cost benefit analysis and ergonomics show that a wind turbine with two or three blades has been proven to be the most efficient and cost effective, when large scale wind turbines and wind farms are considered.[30,53] The use of two blades connected to a rigid hub produces cyclic hub loads, which are normally relieved by employing a teeter hinge that allows see-saw motion to take place out of the plane rotation.[15] The hub nodding moment, which is the largest hub load, is therefore eliminated and over all, the hub loads are reduced by an order of magnitude. Employment of a teeter hinge also reduces the blade loads near the root by approximately 40%.[99] The use of a third blade design has almost the same results as a teeter hinge on the hub moments since the polar symmetry of the rotor averages out the applied sinusoidal loads.[108] Hence, it can be said that, the dynamic behaviour of the tower is very strongly influenced by the choice of the number of the blades. However, three bladed designs are expected to have a reduced reliability level as compared to two bladed designs since more components are used.

B.1.4 The drive Train

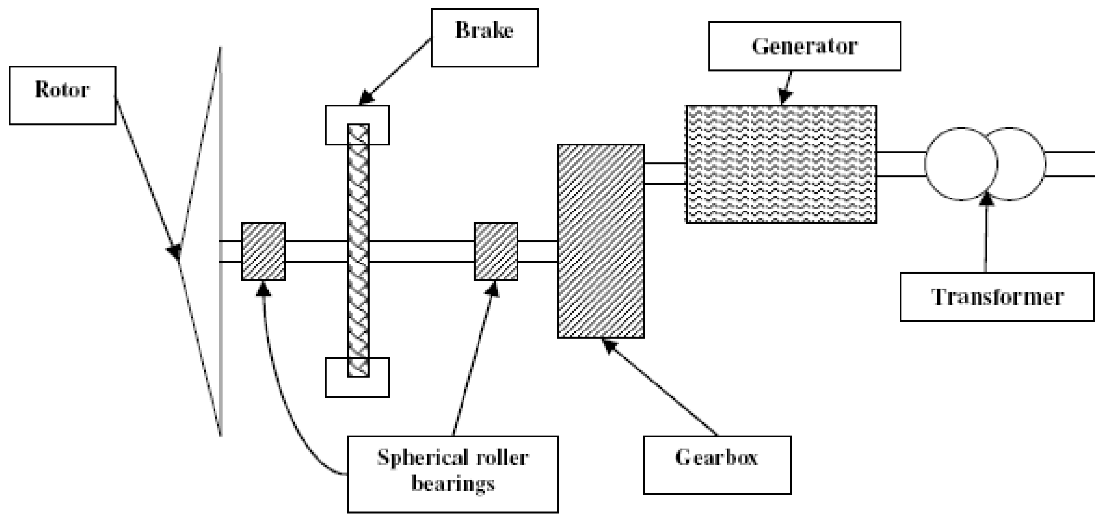
The drive train is made up of components which include all the rotating mechanical parts of the wind turbine, except of the blades. Those parts are the gearbox, if present, the shafts, the bearings and the breaks, as shown in Figure B.5.

Generally two types of gearboxes are used in modern wind turbines, the parallel shaft and the epicyclic or planetary, with the latter being much more expensive.[8] Since the gearbox of the epicyclic type is smaller in size and weight, compared to the parallel one, it is preferred especially when a wind turbine in excess of 500 kW is considered.[108] However, there are a great number of examples of modern large wind turbines the last 3 years, which use a complex combination of the parallel and the planetary gearbox.[30,8] Gearbox efficiency can reach levels of about 95 to 98% depending on the number of shaft stages and on the lubrication type.[108]

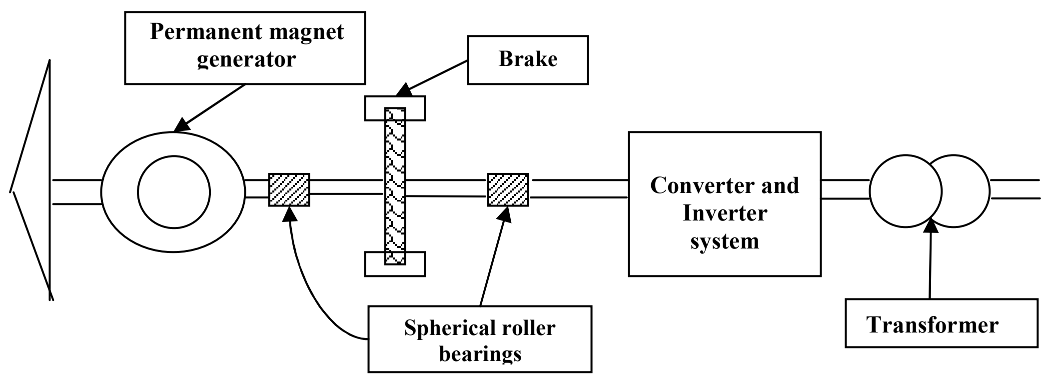
A typical example for wind turbines rated between 300 kW and 2 MW, with upper rotational speeds between 48 and 17 rpm, overall gear ratios of between about 1:31 and 1:88 are required.[53] Normally these large step-ups are achieved by three separate stages with ratios of between 1:3 and 1:5 each.[53]

At present, projects that are trying to eliminate gearboxes, due to weight reduction and increased maintenance attention needed, are in operation or in the last stage of completion,[30] as shown in Figure B.5. These prototypes are mainly focused for offshore applications. Since the introduction of the direct-drive transmission systems, in other words the gearless designs, there has been a big debate over the suitability, the cost reduction and the problem avoidance of such machines over conventional drive trains.[30,53] The elimination of the gearbox has obviously eliminated a lot of maintenance and mechanical problems associated with the gearbox, but could potentially bring problems of electrical nature.[30,53] Nonetheless, the use of a direct drive generator on offshore applications is thought to be of great advantage for two main reasons:

- The reliability when going offshore is expected to be higher, due to the low availability and high mean downtime of gearboxes, as explained in Chapter 4.
- The larger size of the direct drive compared to the conventional one, does not appear as an aesthetics problem to offshore projects.[124]



Geared wind turbine



Direct drive wind turbine

Figure B.5 A typical schematic diagram of geared (top) and direct-drive (bottom) wind turbines.

It is obvious that for such complicated wind rotating machines, effective breaking systems, to stop rotor rotation, have to be installed.[53] As seen in Figure B.5. There are at least two independent systems, each capable of bringing the wind turbine to no-speed condition in a situation like high winds and fire.[99,53] These brakes are fitted on the low-speed shaft of the wind turbine in order not to depend on the integrity of the gearbox of the system.[53]

B.1.5 The Foundations

The foundations are found to be one of the cost drivers of the offshore projects. They can account up to 16% for a moderate size wind farm,[30] this being the reason for strong emphasis given to designing and constructing cost efficient foundations. There are generally two different types of structures that could be applied to offshore wind farms, with a number of sub-categories each:[30]

- Bottom-mounted support structures and
- Floating support structures.

There is yet no criteria on the selection as the floating ones are only in the research and design stage.[126] Nevertheless they pose a strong substitute for future very deep water applications.[30,126] One of the major representatives of bottom-mounted structures is the monopile design, as seen in Figure B.6. It is the most commonly used solution nowadays in the offshore power sector.[30,127] A simple steel tube is driven into the sea bed at a penetration of 15 to 25 meters with the use of a piling hummer, enabling all the lateral and axial forces to be transferred to the sea bed. The pile diameters are about 3 to 5 meters in diameter and they weigh between 100 and 400 tonnes depending on the topology and wind turbine's power rating.[55,61,62]

Furthermore, the gravity based support structure is another solution. The gravity force of a concrete caisson is used to keep the turbine's structure in an upright position. This foundation type is found to be prone to hydrodynamic loading due to the force of the waves passing the structure.[30,36] Two studies on offshore wind turbine foundations showed that this type of foundation is commercially unfavourable in water depths in excess of 10 meters or 20 meters.[55,128]

Another representative of this category is the tripod design, originating from the oil and gas industry. The structure is made of a centre column that carries the tower and the steel space frame in three piles that are driven into the sea bed and connected to the frame through sleeves at the three corners.[7,55] The cylinder between the piles and the pile sleeves is filled with grout after piling to ensure rigid connection. The penetration depths, is similar to the monopile but also depend on the topology.[7,36]

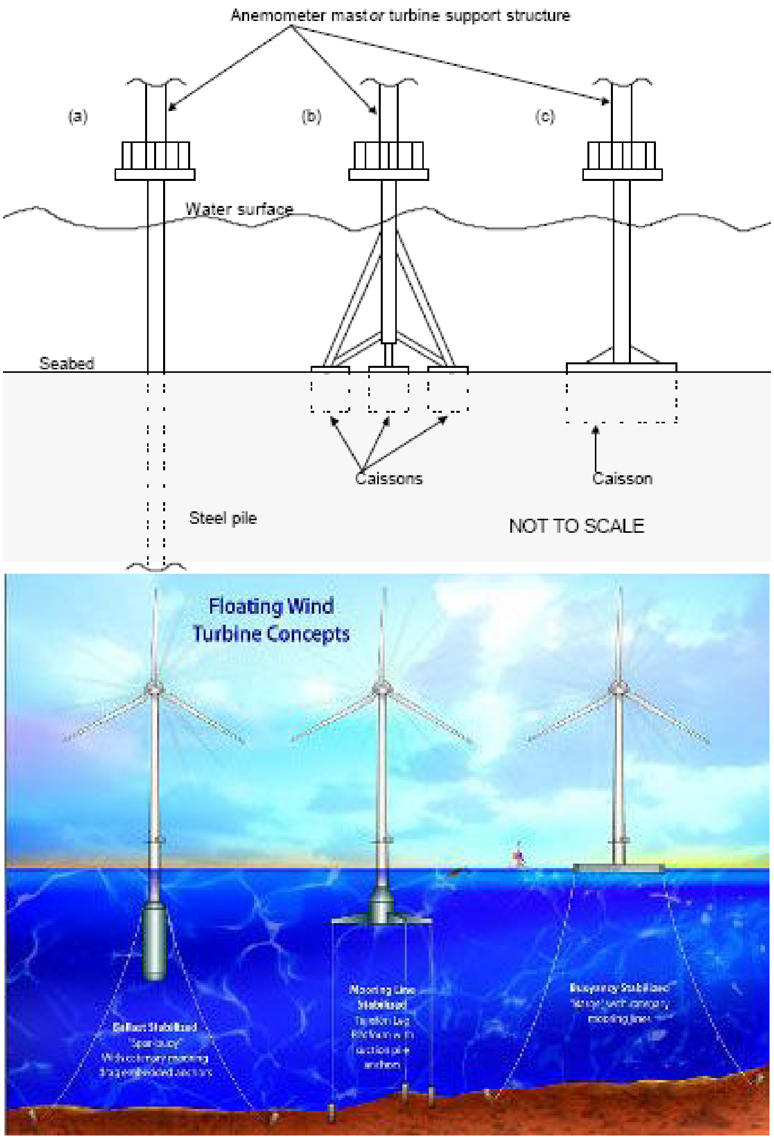


Figure B.6 Different type of foundations for offshore wind farms.[128]

On the floating category of support structures a variety of designs exist that have been proposed, like; the semi-submersible, the buoy type and the multiple unit float.[36] Each one of those have seen great design optimisations over the years but still a simple cost analysis could show that the price of the electricity that would be generated with the use of floating structures is some 40 – 50% larger than conventional bottom mounted turbines.[55,36] The above observation is based upon applying the floating structures to existing offshore wind farms, but the real comparison should be made to very deep waters where floating structures pose their greatest advantage, but conclusive evidence of this analysis does not exist.

B.2 Information on existing offshore wind farms

The first prototype offshore wind farm was built at Vindeby in Denmark, Figure B.7. This project consists of eleven stall regulated turbines of 450 kW power, mounted on reinforced concrete caissons in a water depth of about 5 meters. The turbines have rotors of 35 meters in diameter and are mounted on steel towers. This particular wind farm is located 2 to 3 km offshore, and a 10 kV submarine cable, buried in the sea floor, transports the power back to land. It generates about 12 GWh of electricity per year, which is around 20% higher than an equivalent onshore project. But on the other hand, the overall cost per kWh is approximately 60% higher and the initial cost is 80% higher than the onshore equivalent.[15,127]

Figure B.7 Vindeby offshore wind farm.[129]

Another existing project is the Lely Windfarm, located in the Netherlands, as seen in Figure B.8. It was the first offshore wind farm to be constructed for this country and is located one kilometre offshore while the water depth is around 8 meters. The project consists of four 500 kW turbines with 30 meter high towers. The turbines are twin-bladed with a diameter of 41 meters. These wind turbines have active stall control, which means that they are set at a fixed pitch angle and power is controlled by aerodynamic stall. This project generates 30% more energy than an identical onshore wind farm, located in southern Holland, due to the higher average wind speeds (capacity factor) and reduced turbulence.[15]

Figure B.8 Lely offshore wind farm.[99]

A further project is the Tuno Knob Windfarm, located in Denmark, six kilometres offshore. It consists of ten 500 kW three bladed turbines. These wind turbines are pitch regulated with 40 meters rotor diameter. The towers are 40.5 meters long and the water depth in that area is 3 to 4.7 meters. The operators have published an annual electricity production of 15.2 GWh and the cost of energy is around 4.5 p/kWh.[130]

Figure B.9 Horns Rev, Denmark's largest wind farm.[36]

The largest existing wind farm in Denmark is the offshore wind farm of Horns Rev, which was completed in 2002. It is situated in the North Sea, around 14-20 km off the coast of Jutland. Consisting of 80 2 MW wind turbines, this offshore wind farm has a total capacity of 160 MW, which makes it the largest offshore wind farm in the world today, shown in Figure B.9.[127]

A further large offshore wind farm is Nysted Offshore Wind Farm at Rødsand built in 2003. The wind farm is located approximately 10 km south of the town of Nysted in Holland and consists of 8 rows with 9 turbines each. The total power of the 72 wind turbines each of 2.3 MW thus reaches 158.4 MW. The annual electricity production of the wind farm is enough to supply 110,000 (Danish) households. The wind turbine towers are about 70 m tall, and the rotor blades 40 m long.[15,127]

Furthermore, Bockstigen – Valar in Sweden is located 4 kilometres offshore. It consists of five 500 kW turbines, giving a total wind farm capacity of 2.5 MW. Monopole foundations have been used with the drilling and turbine installation achieved for the first time using a jack-up barge at the site, which has a 6 meter water depth.

Another offshore wind farm is the Middelgrunden, located 2 km off shore east of Copenhagen, as seen in Figure B.10. It consists of 20, 2 MW wind turbines arranged to form an arch. With a total power of 40 MW the wind farm can generate 90 TWh a year. That is equivalent to the annual electricity consumption of 20,000 (Danish) households or three per cent of the total electricity consumption of Copenhagen.

Figure B.10 Middelgrunden offshore wind farm.[131]

North Hoyle is the UK's first major offshore wind farm and represents a major milestone in the UK's drive towards cleaner sources of power. Built in 2003, the project is now fully operational and produces enough clean, green electricity each year to meet the needs of approximately 40,000 homes. This clean generation will offset the release of about 160,000 tonnes of carbon dioxide every year. The project is located 4-5 miles off the North Wales coast between Rhyl and Prestatyn and comprises of 30 wind turbines, each rated at 2 MW.

Scroby Sands is a further offshore wind farm that has been developed in the UK. The wind farm is located 2.5 km offshore Great Yarmouth on the coast of East Anglia. The development comprises 30, 2MW wind turbines, 60-metre high, which is enough to power an equivalent of 41,000 homes in the area.

The Kentish Flats offshore wind farm is a key element of the British Government's commitment to reduce the emission of greenhouse gases. It comprises of 30 wind turbines capable of up to 3 MW each. This project was fully consented in March 2003 and started generating electricity in late 2005.

British and Danish energy groups Centrica and DONG have developed a 90 MW wind farm in the East Irish Sea approximately 7km south west of Walney Island, near Barrow-in-Furness. The project is called Barrow Offshore Wind (BOW). The wind farm comprises 30 wind turbines, each capable of up to 3 MW, delivering power to the existing grid system at Heysham via buried subsea and onshore cables. It is reported that the annual production is 305 GWh, which is capable of supplying around 65,000 homes.

B.3 Accessibility of Offshore Wind Farms

Gaining access to an offshore wind turbine for routine servicing and maintenance is difficult or impossible in harsh weather conditions due to wave heights, wind speeds and poor visibility at night.[12,108,132] The method that is currently used for transporting personnel and light equipment is by small boats or helicopters, which is limited to relatively benign sea states, up to 2 meters of wave height,[132,133] and for heavier components normally jack-up vessels are used.

During the last 15 years that offshore wind turbine industry began its development, a number of alternative solutions to the transportation of personnel and equipment have been proposed and some of them also adopted, as listed below:

- **Helicopter.** The use of helicopters to land on small platforms on the top of the wind turbines. The access to every turbine is easy, fast and can be performed most of the time.[7,55,8] The disadvantages are the high cost, the weather and limitations to transported equipment, due to weight. The use of helicopter for transportation of personnel and equipment was adopted from the offshore oil and gas industry.[7,8] In this industrial sector the cost of using helicopters for transportation means is justified by the large financial losses that the project would suffer from a major failure or simple maintenance downtime.

- **Underwater tunnels.** The capital cost for such a project has to be investigated in detail, before any conclusions could be drawn for its suitability. The design and construction of such a solution requires extensive research and planning on whether it is possible to be built and satisfy the economics of the investment.[8,31]

- **Jack-up boats**. The advantages of such a solution is that this kind of vessel can be raised well above the waves and be stable for the transportation of heavy equipment. On the other hand the disadvantages of a jack up vessel, is the high costs associated for hiring.[8,132] Furthermore, this kind of vessel requires a very stable seabed to rest its legs on along with the fact that it takes 1 to 2 hours for that operation due to safety and insurance reasons for the cable arrays on the seabed.[132]

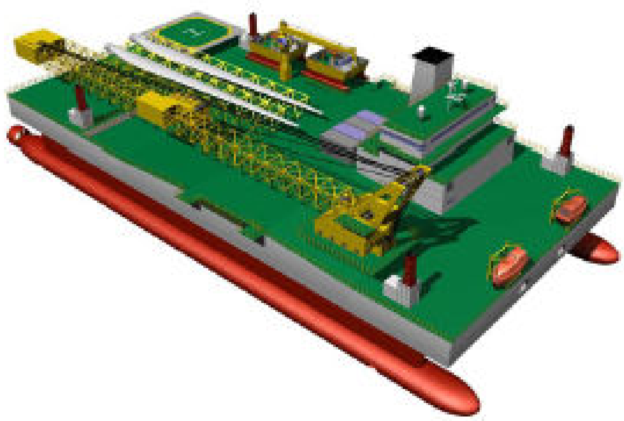


Figure B.11 Swath design from UCL Ship Design Exercise.[134]

- **Swath.** The use of swath support vessels, as shown in Figure B.11. This vessel is capable of economic cruising speed of 10-23 knots and able to transport maintenance technicians to the offshore site. The design incorporates accommodation for 24 personnel and is capable of conducting all the maintenance required, including blade changes with autonomy of 28 days before returning to shore.[134] This solution despite the high initial cost of building the vessel could potentially satisfy the advanced needs in terms of economics, serviceability and accessibility of a very large offshore wind project, but further research is needed in this area.[134]

B.4 Wind Energy Legislation in the UK

The per capita energy consumption in the United Kingdom has risen gradually over the past two decades, the pattern is similar to that of other OECD (Organisation for Economic Co-operation and Development) countries.[8,130] In 2000, per capita energy consumption in the United Kingdom was 166.1 million Btu. This is slightly less than per capita energy consumption levels in France (176.8 million Btu), Germany (170.4 million Btu) and, Japan (171.6 million Btu), and significantly less than in Norway (399.6 million Btu) and the United States (351.0 million Btu).[8,130,135] The United Kingdom has 72.4 million kilowatts of installed electric capacity, about 80% of which is thermal, 18% nuclear, and 2% hydropower.[26,136] The country generated 355.8 billion kilowatt hours (bkwh) of electricity in 2000, making it the third-largest electricity market in Europe (behind Germany and France). In 2001, only 37.2% of UK electricity was coal-fired. The remainder was accounted for by natural gas (31.5%), and primary electricity sources such as nuclear and hydroelectricity (25.8 %).[135,136]

With introduction of the Climate Change Levy in 2001, and its exemption for renewable energy resources like solar and wind, renewable sources of energy are beginning to gain more attention. The United Kingdom hopes to increase the share of electricity generated by renewables from 3% in 2001 to 10% by 2010.[8] Additionally, the British government is investing over \$364 million over the next three years into renewable energy sources including solar, biomass and wind.[137] Over the next two years, the UK hopes to add an additional 400 MW generation capacity, and to have 15% of its electricity generated through (mostly offshore) wind turbines by 2020.[8,136] The Non-Fossil Fuel Obligation (NFFO), created by the Electricity Act of 1989, is the primary piece of legislation providing a premium-price, market-enabling mechanism which attempts to encourage renewable-based electricity generation.[54] Under the NFFO system, the difference between the premium price paid to “green” electricity suppliers and the market price is financed by the Fossil Fuel Levy, a tax paid by licensed electricity suppliers and ultimately passed on to consumers.[54,8]

B.5 Wind Turbine Component Costs

Tables B.1, B.2 and B.3 give the costs of wind turbine components for different wind turbine power ratings. These tables along with a study on the component cost for scaling-up issues of wind turbines[87] have been used for the calculation of the repair costs of wind turbine components, as has been suggested by a DOWEC, RECOFF and Opti-Owecs projects.[69,70,71,72,73,138] It could be observed from these tables that the cost of each component depends on the size of the wind turbine and the technology used.

Table B.1 The percentage of wind turbine component cost for two different wind turbine power ratings.[41]

	750 kW (stall controlled) wind turbine	**1500 kW (variable speed) wind turbine**
Components	**Percentage of component cost (%)**	
Rotor blades	34	21
Rotor hub	2	2.1
Blade bearings	-	3.1
Blade-pitch mechanism	0.8	4
Rotor shaft	2.7	2.6
Rotor bearings and housing	1	1.7
Gearbox	12.5	13.6
Nacelle housing	8.7	4.7
Yaw system	2.4	3.4
Nacelle fairing	2	1.6
Miscellaneous (rotor brake, generator shaft, clutches, heat exchangers)	5	3.2
Generator and converter	7.5	10.9
Control system	5	7.4
Tower	16.4	20.7
Total	100	100

Table B.2 The cost of wind turbine component for two different wind turbine power ratings.[41]

	750 kW (stall controlled) wind turbine	**1500 kW (variable speed) wind turbine**
Components	**Actual cost of components**	
Rotor blades	102,300 (3 blades)	198,000 (3 blades)
Rotor hub	6,000	20,000
Blade bearings	-	28,800
Blade-pitch mechanism	2,500	30,000
Rotor shaft	8,050	24,500
Rotor bearings and housing	3,000	16,000
Gearbox	37,600	128,000
Nacelle housing	26,000	44,000
Yaw system	7,200	32,000
Nacelle fairing	6,000	15,000
Miscellaneous (rotor brake, generator shaft, clutches, heat exchangers)	15,000	30,000
Generator and converter system	22,500 (50% each)	102,500 (50% each)
Control system	10,000	30,000
Electrical system	37,500	172,500
Tower	50,000	195,000

Table B.3 The cost of different wind turbine component for 3 MW wind turbines.[119]

	DDSM	DDPM	GPM	GDFIG	DFIG
Generator dimensions					
Stator radius r_s (m)	2.5	2.5	1.8	1.8	0.42
Stack length l_s (m)	1.2	1.2	0.4	0.6	0.75
Number of pole pairs p	40	80	56	40	3
Number of slots per pole per phase q	2	1	1	2	6
Air gap g (mm)	5	5	3.6	2	1
Stator slot width b_{ss} (mm)	15	15	15	11	12.9
Stator tooth width b_{st} (mm)	18	18	19	12.5	11.5
Stator slot height h_{ss} (mm)	80	80	80	60	60
Stator yoke height h_{sy} (mm)	60	40	40	50	100
Rotor slot width b_{rs} (mm)	-	-	-	10	10
Rotor tooth width b_{rt} (mm)	-	-	-	12.5	11.5
Rotor slot height h_{rs} (mm)	-	-	-	60	60
Rotor yoke height h_{ry} (mm)	60	40	40	50	100
Pole/magnet height h_p / l_m (mm)	140	15	15	-	-
Rotor pole width b_p (mm)	137	79	82	-	-
Generator parameters					
Main inductance L_m (mH)	46	4	0.88	17	99
Stator leakage induct. $L_{s\sigma}$ (mH)	8.2	7.3	1.4	1.7	0.99
Stator resistance R_s (mΩ)	119	88	22	44	26
Rotor leakage induct. $L_{r\sigma}$ (mH)	-	-	-	1.8	1.2
Rotor resistance R_r (mΩ)	-	-	-	48	35
Generator active material weight					
Iron (ton)	32.5	18.1	4.37	8.65	4.03
Copper (ton)	12.6	4.3	1.33	2.72	1.21
PM (ton)	-	1.7	0.41	-	-
Total (ton)	45.1	24.1	6.11	11.37	5.25
Cost (kEuro)					
Generator active material	287	162	43	67	30
Generator construction	160	150	50	60	30
Gearbox	-	-	120	120	220
Converter	120	120	120	40	40
Generator system cost	567	432	333	287	320
Other wind turbine parts appr.	1300	1300	1300	1300	1300
Margin for company costs	250	250	250	250	250
Total cost	2117	1982	1883	1837	1870
Annual energy					
Copper losses (MWh)	454	189	48	229	82
Iron losses (MWh)	40	87	119	119	68
Converter losses (MWh)	380	370	358	121	120
Gearbox losses (MWh)	-	-	264	264	527
Total losses (MWh)	874	647	789	734	798
Energy yield (GWh)	7.74	7.89	7.70	7.76	7.69
Annual energy yield / total cost					
(kWh/Euro)	3.67	3.98	4.09	4.22	4.11

B.6 Wind Turbine Component Failure Modes and preventive maintenance tasks

This Appendix gives details of the wind turbine failure modes for the major components and the preventive maintenance tasks for wind turbines.

B.6.1 Electrical Control system failures

The control system consists of a large number of small, interconnected components that are likely to have been supplied from numerous manufacturers, which could result in the reported high failure rate of the electrical system.[139] Some of the failures that might occur include: microprocessor errors, wire break/loss of signal, over/under temperature trips, scaling and offset errors of transducers including drift, loss of input signals, mechanical damage, over/under frequency, over/under voltage.[139] The wind vane and anemometers will be particularly susceptible to harsh weather conditions experienced at the marine environment.

B.6.2 Gearbox failures

Gearbox failures include offset of tooth wheels, tooth wear, pitting and deformation of outer face and rolling elements of bearings, fatigue and impending cracks of shafts.[141] Maintenance of the gearbox is imperative if a long service life is to be achieved, while the gearbox lubricant must be kept contaminant free.[140] The use of a motor to preheat the oil of the gearbox is often used which is a further component that could suffer from failures and appropriate maintenance should also be applied.

B.6.3 Yaw system failures

Yaw systems are either actively or passively controlled. Active yaw systems tend to have higher maintenance costs associated with them due to dynamic loading through continually adjusting the direction of the wind turbine to match the anemometry signals.[145] Yaw system failures are generally associated with the yaw drive motors, the azimuth bearing, the pinion gears and yaw angle offset.[145]

B.6.4 Generator failures

Faults in generators are often caused by uneven air gaps between the rotor and stator, damage to the stator windings or insulation, damaged rotor bars, bad solder joints and loose connections and slip ring and brush-gear defects.[145,50] The failure modes of the generator will be influenced by mechanical, electrical and environmental operational conditions, e.g. bearing damage can be caused by pulsating loads or drive train vibrations transmitted to the generator, windings may be damaged by repeated application of high starting forces.[145,50]

B.6.5 Hydraulic failures

Hydraulic systems are used within the wind turbine for controlling disc and tip brakes and the yaw brake system.[145] The brakes are applied by a release of pressure using magnetic valves. Hydraulic failures may be caused by valve malfunction or from leakages or blockages in the hoses and filters.[145]

B.6.6 Wind turbine electrical system

Failures may occur in the electrical system power electronics (variable speed turbines) (similar to the control system items), in capacitor bank switching (fixed speed turbines) or in transformers (if present in the wind turbine).[142] Transformer failures may be caused by problems such as lines surges, deterioration of insulation, moisture ingress, lubrication oil contamination or loose connections.[142]

B.6.7 Wind farm electrical system

Failures can occur in the wind farm cabling, substation transformer, switches and surge protection equipment. If fitted, there is a slim chance of failures occurring in the wind farm supervisory control system.[145]

B.6.8 Grid failures

Turbines are fitted with protection equipment that monitor the state of the grid (primarily voltage and voltage imbalance) and may require that the turbine either disconnects from the grid or shuts-down if a fault state is detected.[145] This could be due to transmission line tripping (due to overload or item failure), loss of production capacity elsewhere on the network causing under-voltage or short circuits.[145]

B.6.9 Blade failures

The majority of wind turbine blades are made of composite materials. Degradation of the laminations or in the binding adhesives can be caused by water, sunlight and chemicals in the atmosphere as well as from fatigue.[144] High stress concentrations will also be seen at the blade root and the interface where the blade connects with the hub and are more likely to be susceptible to failure. Faults are also likely to occur with the pitch adjustment and the tip brakes.[144]

B.6.10 Preventive maintenance tasks

The different types of preventive maintenance and routine periodic tasks and inspections for wind turbines are listed below:[161]

1. A check of the gearbox and hydraulic system oil levels.
2. Inspections for oil leaks.
3. Inspections on the cables running down the tower and their supporting system.

4. Observation of the machine while running to check for any unusual drive train vibrations.
5. Inspections of brake disks and brake adjustment.
6. Inspections of the emergency escape equipment.
7. Checking the security of fixings, e.g. blade attachment, gearbox hold down, yaw bearing attachment.
8. Checking high speed shaft alignment.
9. Checking performance of yaw drive and brake.
10. Bearing greasing.
11. Oil filter replacement.
12. Inspecting overspeed protection systems.
13. Blade cleaning from gradual build up of dirt.

C. Weather and Sea State Data for the UK and North Sea

The figures in this Appendix show the average weather and sea state conditions for different months throughout the year for the UK and the North Sea. A pattern for the winter and summer months through the years can be observed from the graphs presented below. Figures C.1, C.2 and C.3 present the average data collected for the UK and Figure C.4 present the average data for the North Sea. Considering the fact that the offshore wind farms are reported to be accessible only when wave height are lower than 2 meters,[10,42] it can be observed in Figures C.1, C.2 and C.3 that between November and April the average wave heights exceed the limit of 2 meters and the accessibility to offshore wind turbines becomes very difficult or even impossible, whilst for the period between May and October there is a yearly pattern on the wave heights that do not exceed 2 meters, therefore allowing the access to offshore wind turbines. Figure C.4 shows a similar pattern, as observed for the UK, for the average wave heights between the summer and the winter months for the North Sea.

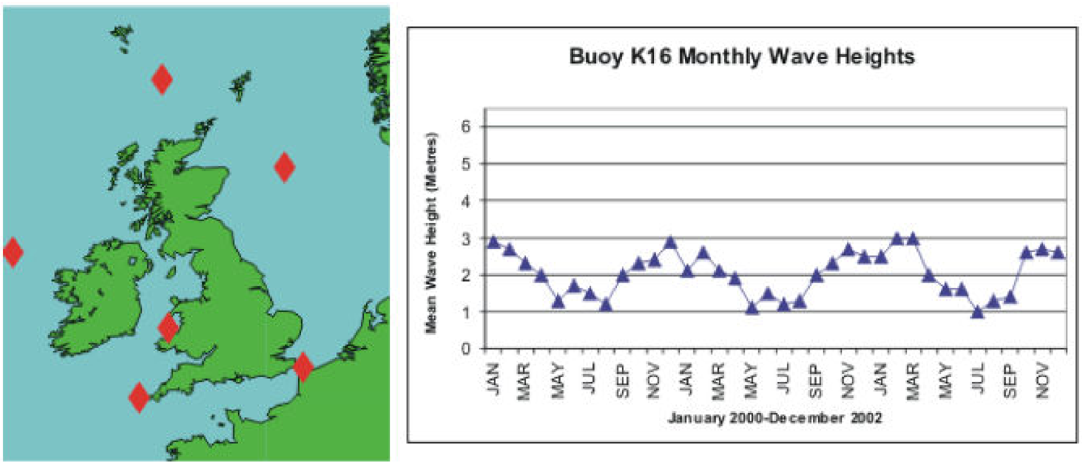


Figure C.1 Wave data for 2000 – 2002 at selected stations of the Met Office's Marine Automatic Weather Station (MAWS) Network for the UK.[146,147]

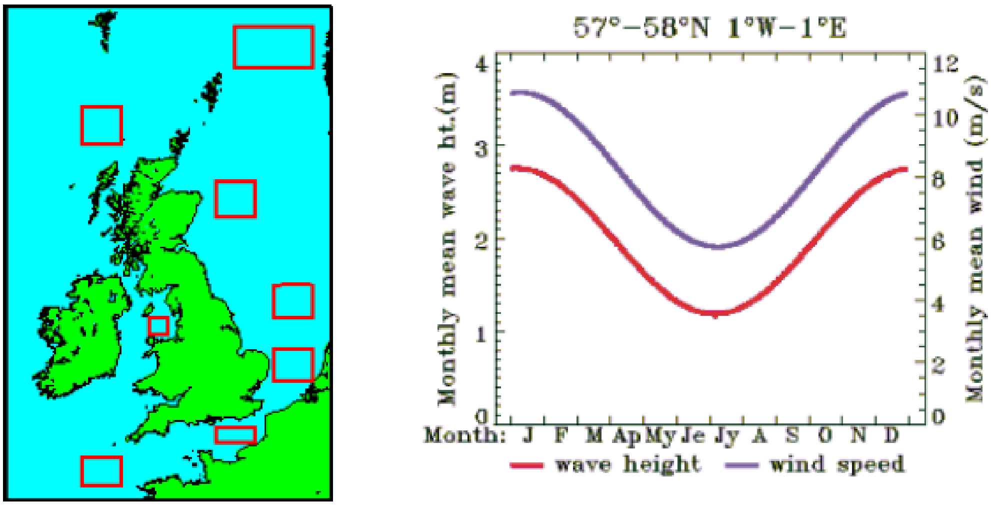


Figure C.2 Monthly mean wave heights and wind speeds derived from satellite altimeter data from 1985 onwards for the UK.[146,147]

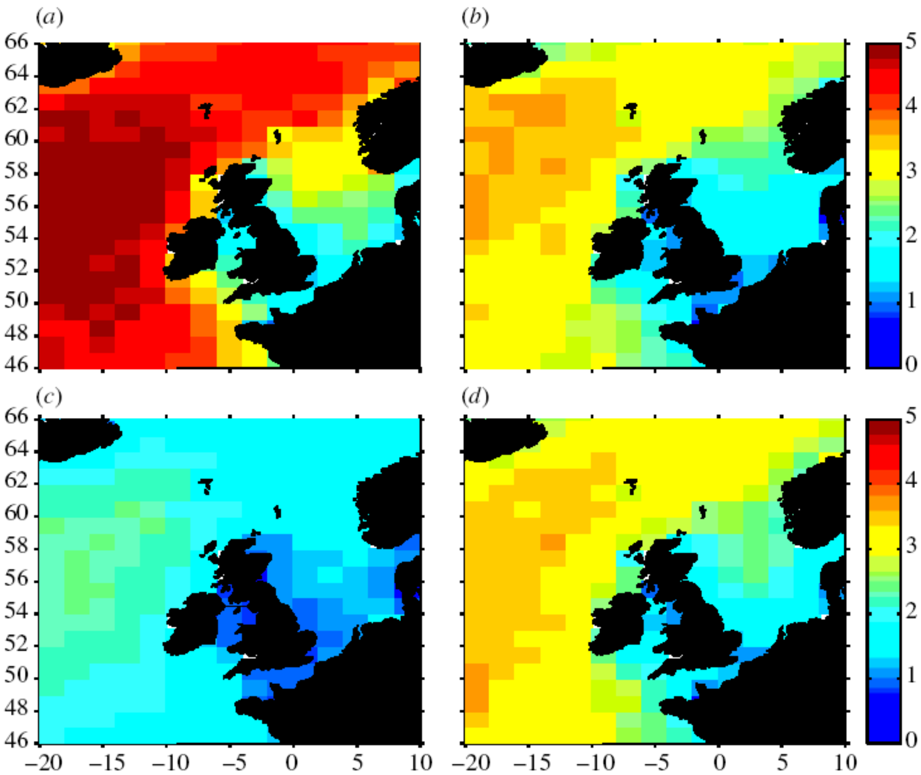


Figure 1. The mean significant wave height (metres) in the four seasons.

Figure C.3 Mean significant wave height in the four seasons for the UK waters. Graph A represents winter months, graph B Spring months, graph C summer months and graph D Autumn months.[146,147]

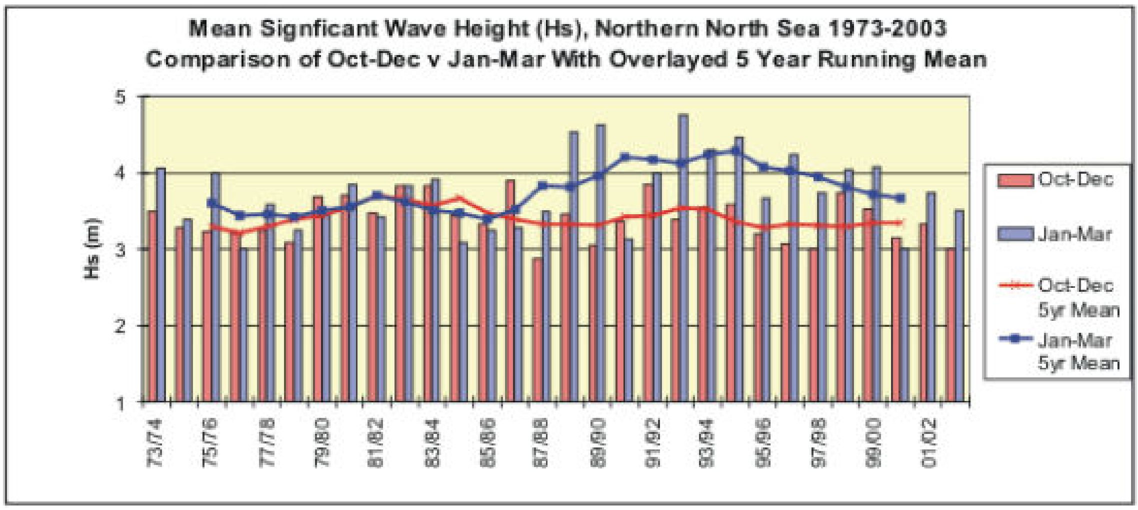


Figure C.4 Mean significant wave height in the Northern, Central and Southern North Sea.[146,147]

D.1 Technical differences between Onshore and Offshore Wind Farms

Work in the offshore environment is reported to be more expensive than equivalent procedures on land, despite the fact that the recent years, actions have been undertaken by the EU to mitigate this problem, with tax relaxations and simpler planning procedures.[55,61,62] Wind turbine marine construction equipment can be difficult to secure and attracts rental charges that show a considerable premium over land based equipment. [61,62,148] Offshore lifting and transport operations are slower and require greater manpower than onshore. Turbines and ancillary equipment must be built to withstand demanding marine conditions and are consequently costly, as compared to those used onshore.[61,62,148] Furthermore, when considering offshore wind farms there are two processes that do not apply to onshore wind farms and make the installation even more difficult and expensive:

- The preparation of the sea bed for the foundation. Before the foundations are installed offshore, the sea bed has to be treated and transformed to accommodate the base of the offshore wind turbine. This process is expensive and time consuming, because there is always the factor of sea bed uncertainty.[149]

- The planning permission for the establishment and installation of transmission cables.[149] From installation experience this process is difficult enough to make the offshore projects unique, as compared to onshore wind farms.[149]

In addition to the above disadvantages, the operation of an offshore wind farm is greatly dependant upon the wind and wave conditions.[10,42] From the existing offshore project operators' experience, Van Bussel (1997)[10] reported that an offshore wind farm may not be accessible for maintenance for a period of one or two months during the winter season. It has also been noted that for wave heights above 2 meters the offshore wind turbine is inaccessible by vessels, for health and safety reasons.[10,7,14] This potentially decreases the availability of the offshore wind farms, reducing the power output of the project.[10]

Consequently, the above disadvantages of offshore applications compared to onshore lead to increased capital and maintenance costs.[69,74] The above observations are the factors that make the offshore projects more expensive than onshore and this reflects in the cost of energy produced.

However, the advantages for going offshore are more significant than the disadvantages, as explained below:

- **Local authorities**. The biggest hold back of continuous development in wind power in the EU is the planning delays.[8,148] Authorities in the UK report that it will be impossible to grant consent for an onshore wind farm in excess of 70 – 80 turbines.[32] The reasons are based on the local authorities objecting developments for aesthetic reasons and limited area allocation for the project.[8,32] This holdback in the development of onshore wind farms has given a great boost to the offshore wind energy sector, where the above problems do not apply.[32],[7] A recent example of the above disadvantage is that the Scottish Government has turned down an application to build a 181-turbine onshore wind farm on the Isle of Lewis in April 2008.

- **Wind speeds**. The wind speeds are considered to be much higher than those on-land and show less variability and gustiness, as there are no obstacles and uneven landscape, resulting in higher efficiencies, compared to onshore wind farms.[30,55] A measure of the windiness of a specific site is the capacity factor of the wind farm, in other words the ratio of actual energy produced by the wind turbine over the theoretical maximum energy production. Figure D.1 gives the capacity factors of the existing offshore wind farms, having an average of 34.2%, in comparison to the onshore wind projects which is between 18 and 28%.

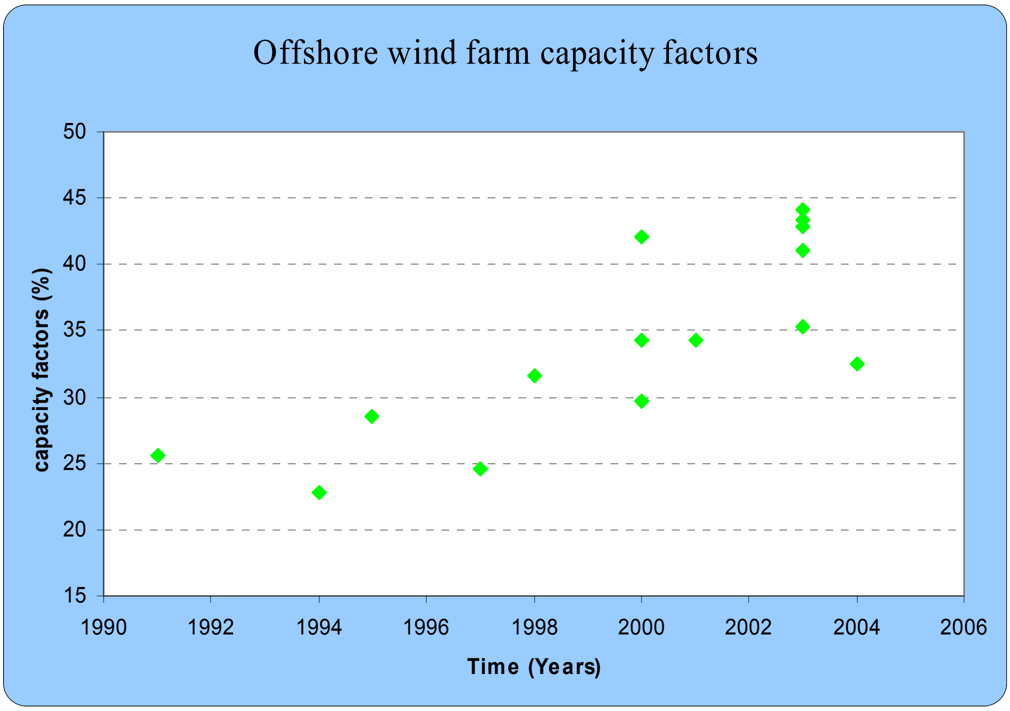


Figure D.1 Offshore wind farm capacity.[121]

- **Aesthetics and Noise**. Although most people are generally in favour of wind energy.[61,62] controversy over the visual impact of wind turbines has been one of the main obstacles to onshore wind farms in the EU, and especially the UK. Apart from objections over visual impact, most objections to wind turbines have been for the noise they generate.[8] While the impact of audible noise is a very subjective experience, operators of onshore wind turbines normally attempt to minimise this disturbance by operating the wind turbine at lower than optimum speed.[55,61,62] In the offshore environment, noise is of a far less concern, hence wind turbines can be operated at optimum speed to maximise power output.

The above factors taken together show a large potential of offshore energy resource and this is particularly important when considering the current EU energy policy context which exploits renewable energy developments to reduce CO_2 emissions.[55] All the above observations show that the future of wind farm development is highly probable to envisage the offshore wind resources when considering the EU member countries, which can be observed in Figure D.2, where the offshore wind farm development since 1991 is presented.

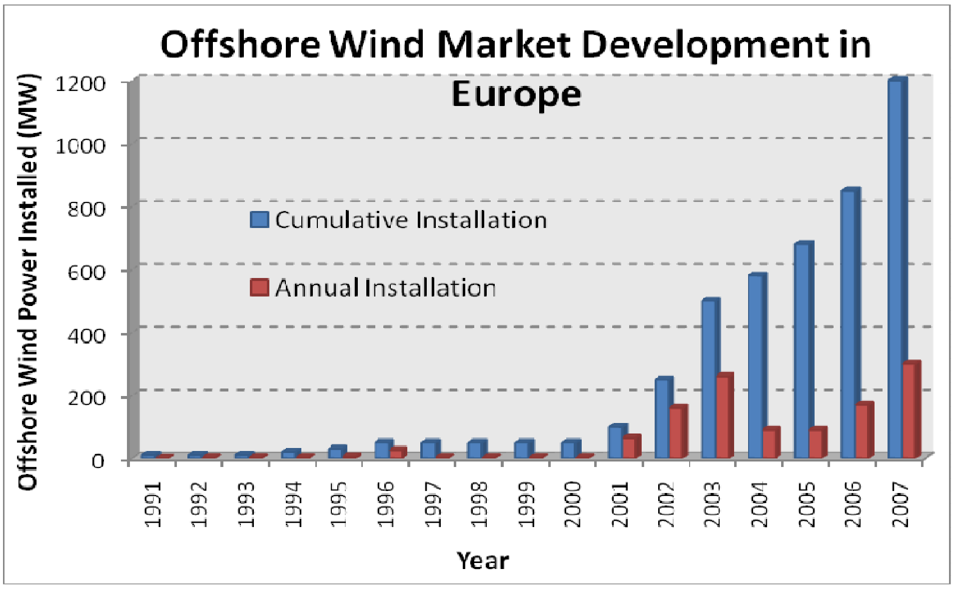


Figure D.2 Offshore Wind Market development 1991 – 2007.[150]

D.2 Financial differences between Onshore and Offshore Wind Farms

The global wind power installations onshore and offshore had reached a level of over 90,000 MW by 2007,[61,62] and close to 120,000 in 2008, as seen in Figure D.3. Within EU the country that is leading in wind energy installation is Germany.

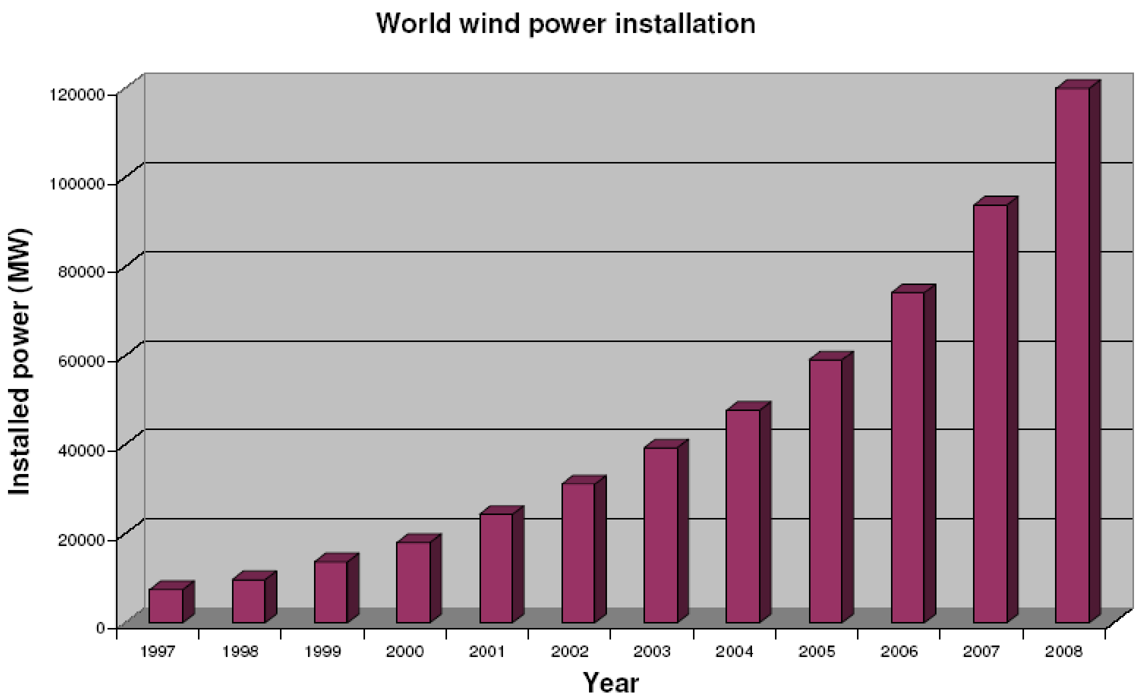


Figure D.3 World's capacity of wind turbines.[61,62]

The costs of constructing a wind turbine varies, as seen in Table D.1, and are largely dependant upon the size of the wind turbine, the location and the site orientation.[30,53] For instance, the cost of the tower and foundations for an onshore wind turbine located on a site easily accessed, is 10% of the total cost, while for an offshore wind turbine the foundations and tower costs can be as high as 20%, as seen in Table D.1.

The unit costs of electricity production from wind generators are not determined by wind turbine cost alone, there are additional costs when planning for the site of the wind farm, along with the site facilities and grid connection.[53,108] The time needed to obtain all the necessary planning permissions for a proposed offshore wind farm, along with the costing of the associated process, is one of the main problems for the offshore wind industry, as explained by the president of BWEA (British Wind Energy Association).[55,137]

Table D.1 Large modern wind turbine component average cost breakdown in percentage of total[7,120,108]

Component	Onshore (%)	Offshore (%)
Rotor	15-25	20-30
cables	5	10-15
Generator	5-10	5-15
Tower and foundations	10	20

When considering an offshore wind farm the economic factors change compared to onshore, giving more emphasis to the location of the project.[8] The cost breakdown between onshore and offshore wind farms, as seen in Table D.2, is very different. Consequently the key factors for early break even point and financial viability of the projects differ greatly. The above observation becomes more complex after the installation of the wind farm, as wind turbine capital costs and operation and maintenance costs interact in very complex ways.[8,71]

Table D.2 Cost breakdown for large onshore and offshore wind farms.[98,8,53,108]

Component	**Onshore (%)**	**Large Offshore (%)**
Turbines	71	51
Grid connection	7.5	18
Foundations	5.5	16
Internal electrical grid	6.5	5
O and M facilities	0	2
Project management	2.5	4
Miscellaneous	7	2

Site costs, are determined by accessibility, foundation conditions and the distance from grid connection points, mainly in offshore applications.[55,8] It is expected that remote locations offshore will have higher installation costs and grid connection costs than more accessible ones, near-shore. In addition, the operation and maintenance practices will be more difficult and expensive, while the wind farm's availability will be lower. All these factors should be greatly considered when comparing the costs of onshore and offshore projects.

E.1 Onshore Wind Turbine Failure Rate Analysis

The following paragraphs explain the investigation on the reliability levels of components of onshore wind turbines. More than 9,500 onshore wind turbines will be analysed by using a number of different databases presented below, for three case-studies; Denmark, Germany and Sweden. The analysis that follows explains the use of the failure rate data from the databases to find an average value for each of the three case-studies on investigation.

Table E.1 The failure rate databases used, listed in order of related country.

Country	Databases used
Germany	WindStats, WMEP, LWK
Denmark	WindStats
Sweden	Felanalys, DV

The databases used for each of the country case-studies, as seen in Table E.1, have some fundamental similarities but also differences between them, and an explanation of them will help interpret and explain the data analysed further in this Appendix:

- Failures of wind turbines, as reported in all the databases, are gathered for each wind turbine without giving details of the failure modes, making it difficult or impossible to comment on the severity or consequence of each failure.[81]

- The period of data collection differs between the databases. The duration of each database is reported in the following tables of this chapter.

- A variety of wind turbines is included in each database in terms of power rating and operating year. For this reason an analysis is made between the failure rates of wind turbines and their power rating and operational year.

- Each country's case-study is treated separately for the reliability analysis and the details of the different databases used in each case are explained.

E.1.1 Germany case-study

Germany is the country with the largest number of operating wind turbines in the world,[41] which indicates that it is a good candidate for wind turbine reliability studies. Two major studies have been performed for the German case-study aimed at obtaining more detailed knowledge on the failures of wind turbines, and their details have been assessed in the following paragraphs.[81,79] Both studies[81,79] make use of the "Wissenschaftlichen Mess- und Evaluierungsprogramm" (WMEP) database; however the second study uses also the WindStats and the LWK (Landwirt-schafskammer Schleswig – Holstein) databases.[151,70,71] The details of each database in terms of turbine population and survey duration are shown in Table E.2 below:

Table E.2 Database details for Germany.[46,50,81]

Database	Number of turbines	Duration survey
WindStats	4000	1994-2004
WMEP	1435	1998-2007
LWK	350-650	1999-2000

To compare the results obtained from the three databases in Germany Figure E.1 is constructed, which gives the percentage of total failure rates for all major components of an onshore wind turbine, and by observing the graph, two fundamental conclusions can be drawn:

a) Considering the wind turbines with higher power rating then their failure rates are found to be higher, as compared to the power rating wind turbines, this being explained by the fact that the wind turbines with higher power rating are newer and consisted of modern technological systems, as compared to older more mature and reliable designs.[46,50,81] The new wind turbine designs are still in the process of evolving to a more mature and reliable technology.

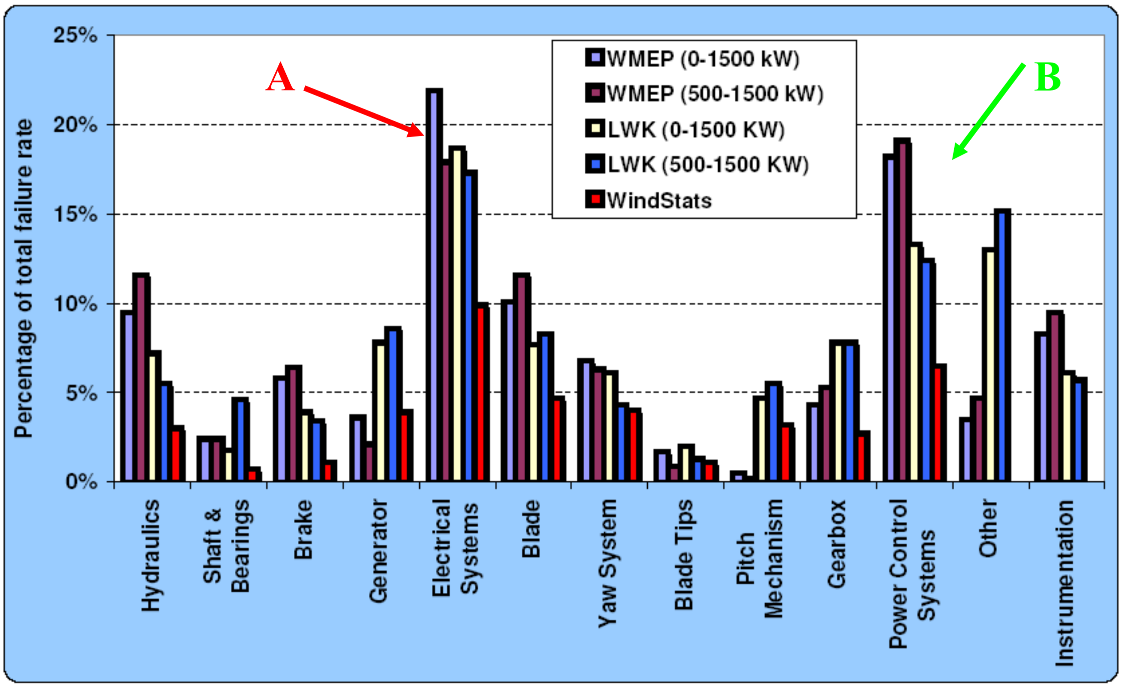


Figure E.1 Summary of failure rates as percentage of total from all the databases for Germany case-study per component. Different wind turbine power rating ranges are presented for each database to distinguish large and smaller wind turbines.

b) The components that suffer the highest failure rates are the electrical systems and the power control units, as seen in Arrows A and B in Figure E.1. Each of these components contributes between 15 to 23% of the total failures of a wind turbine. This observation shows that further investigation is needed into these components, in order to help increase the reliability of future wind turbines.

A large part of the WMEP database (ref ISET), from year 2002 to 2006, has been acquired and assessed in detail, in pursuit of the verification of the graphs reported by the other databases and conclusions drawn for the case-study of Germany. Figure E.2 gives the analysis done based on the details of the acquired part of the WMEP database.

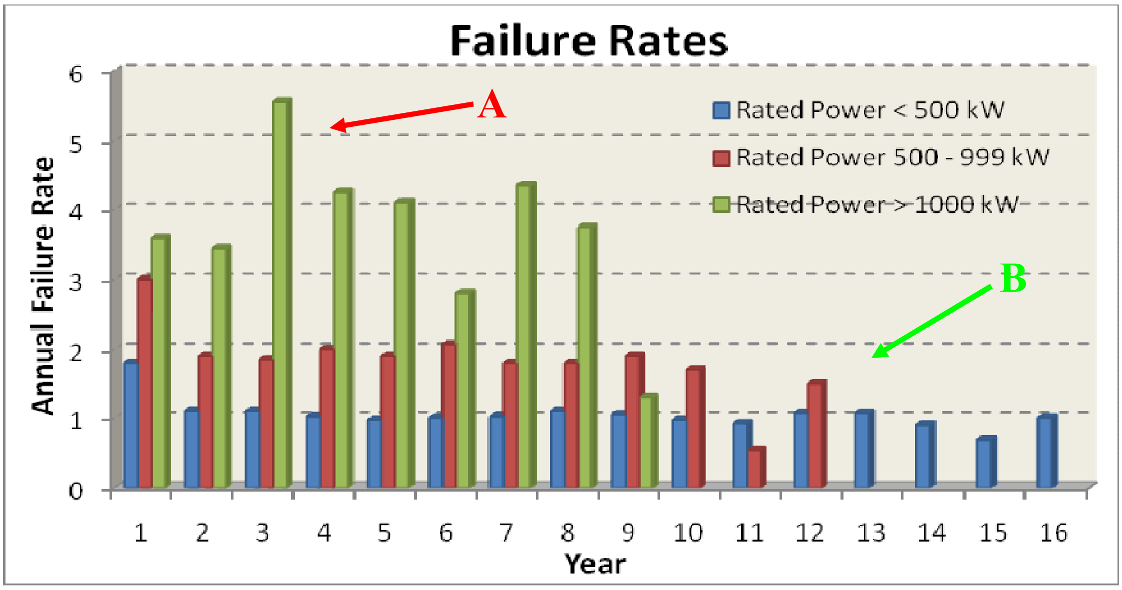


Figure E.2 Failure rates of wind turbines for different power rating ranges and over 16 years of operation.[79,81]

Considering Figure E.2, it can be observed that the failure rates of wind turbines depend not only on their operational age but also on their rated power. Three categories of wind generators are presented in this figure; 500 KW, between 500 to 999 KW and above 1000 KW. The group of mega-watt wind turbines show a significantly higher failure rate, which on the other hand declines by increasing operational age.

Figure E.3 shows the consequences of component failures for the wind turbines with a database of events for more than 15 years. It is clear from this figure that approximately 80% of the failures of the components will cause the wind turbine to stop operating, either because a critical component has suffered a critical failure or the monitoring system has indicated vibrations or noises that exceed the normal operating conditions, resulting in the stoppage of the wind turbine to prevent catastrophic failure of the component until the next maintenance visit.

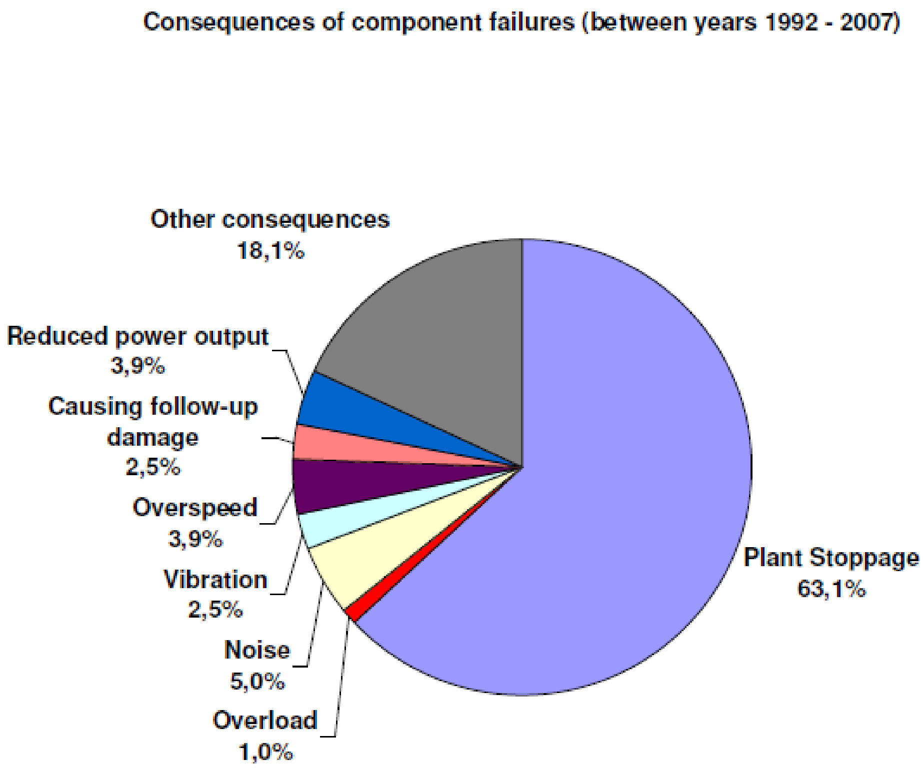


Figure E.3 The consequences of wind turbine component failures (between 1992 – 2007).[79]

Furthermore, from the assessment of WMEP database, a number of important observations can be drawn, validating the findings of the other databases used for German case-study:

- The larger wind turbines in power rating experience higher failure rates, as seen in Arrow A in Figure E.2 due to the use of new and immature technology in terms of reliability.[46,50,81]

- The wind turbines of smaller power rating in Figure E.2 show almost a constant failure rate throughout the range of operational years, with only a small reduction observed in the last years of operation, as seen with Arrow B in Figure E.2.

- Even though the number of large wind turbines participating in the WMEP program of the database is smaller compared to the lower power rating wind turbines; their failure rates are much higher.

E.1.2 Sweden case study

The Swedish wind power industry has expanded rapidly during the past few years. This had a negative effect on producing reliable wind turbines, as the new designs installed are not as mature as older designs.[80] However, two studies using Swedish failure rate data have been analysed and the sources of these data are two; the Driftuppfoljning av vindkaraftverk from Elforsk[156] and the Felanalys from Vattenfall Power Consultant.[157] The details of these two sources are summarised in Table E.3.

Table E.3 Database details for the case-study of Sweden.[80,156,157]

Name of Source	Driftuppfoljning av vindkaraftverk	Felanalys
Time span of data in survey	1997 - 2004	1989 - 2005
Number of turbines in survey (2005)	723	786
Accumulated number of reported failures	1658	1658

Figure E.4 gives the failure rates of the major items for onshore wind turbines in Sweden. The difference this graph has with the one presented for Germany (Figure E.1) is that the sensors and the power control system are shown as two different items. By taking them together and adding to that the failure rates from the electrical items, we get 35% of the total failures of the wind turbines, a value that shows similar magnitude in the German case-study (30-40%). This observation shows that a problem can be identified with the power control and electrical systems of the wind turbines for both the Swedish and German case-studies.

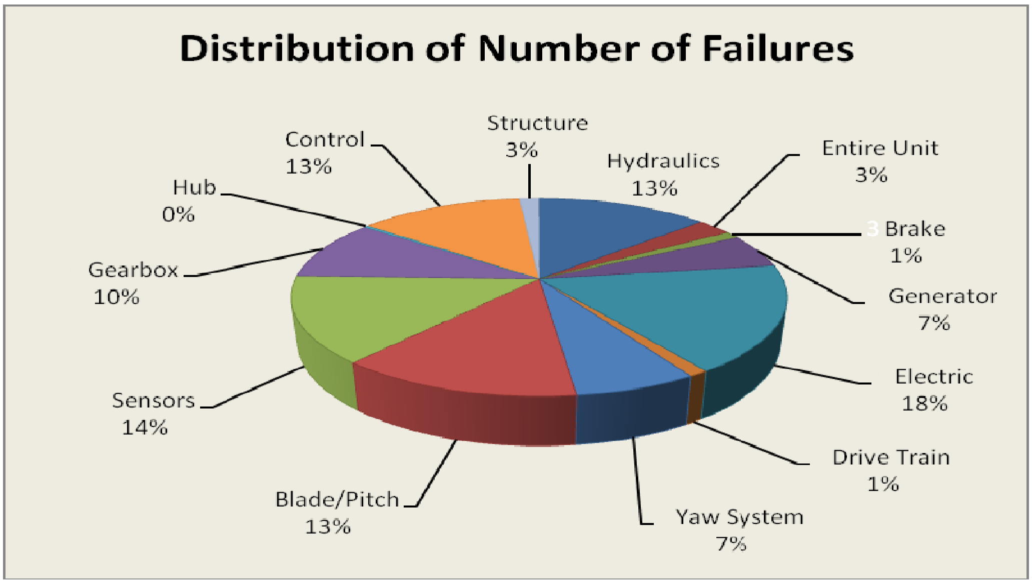


Figure E.4 Failure rates of wind turbines as percentage of total, per item, for Sweden case-study.[80,156,157]

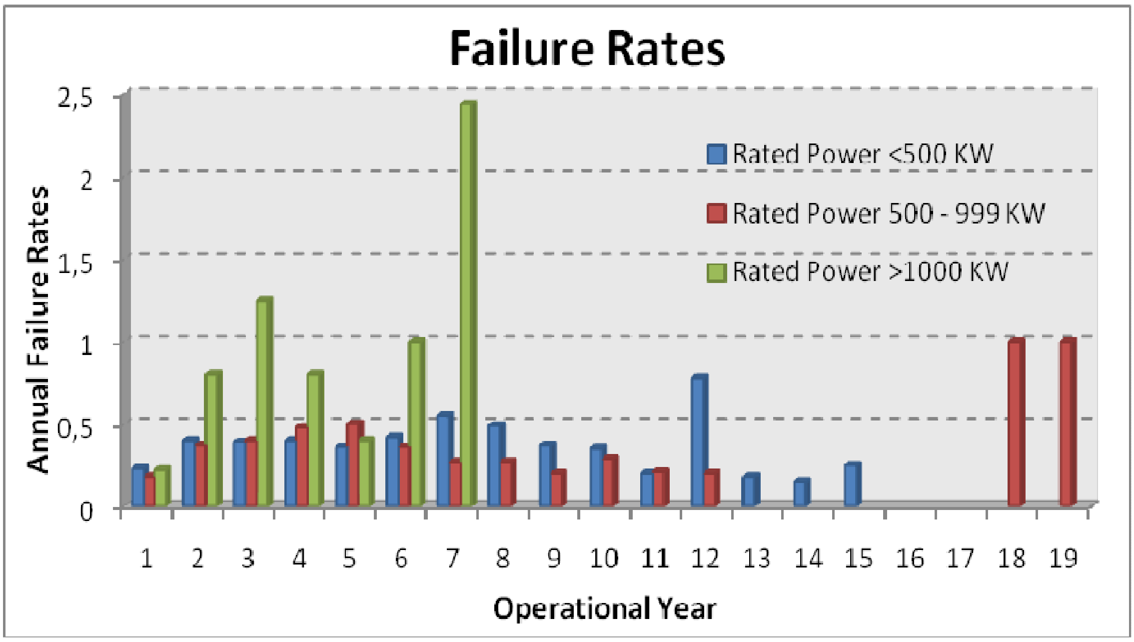


Figure E.5 Failure rates of wind turbines for increasing operational year, categorized by rated power for the Sweden case-study.[80,156,157]

Similarly, as in the German case-study, a comparison of failure rates with respect to the rated power versus the operational year of the wind turbines is given in Figure E.5.

It can be observed in this figure that the failure rates of the large wind turbines rated 1000 KW and above, have significantly higher values than those of the wind turbines of lower power rating ranges, which follows a similar trend as in the German case study. It can also be seen that the failure rates are reduced as the operating period is increased, a fact that was not observed in the German case-study.

E.1.3 Denmark case study

The Danish wind power industry despite the fact that it goes many years back only a few reports have been published regarding the reliability of its wind turbines. The basic source of data for the Denmark reliability analysis is provided by the WindStats database. The details of this database are shown in Table E.5.

Table E.5 Database details for the case-study of Denmark.[46,50,81]

Name of Source	**WindStats**
Duration of Survey	1994 - 2004
Number of wind turbines in survey	2000

Despite the fact that in the two previous reliability analysis case-studies for Germany and Sweden the most problematic wind turbine systems were the power control and electrical system, however in the Danish case-study because of the way the data is collected and presented, the same observation can not be directly concluded. As it can be seen in Figure E.6, the control system shows a very high failure rate, however the failure rate related to the electrical systems is not visualized in the figure as an individual category, but integrated into the ‘other’ category. This can therefore be justifiably assumed as the reason why the category marked as ‘other’ shows the highest failure rate value of 40%.

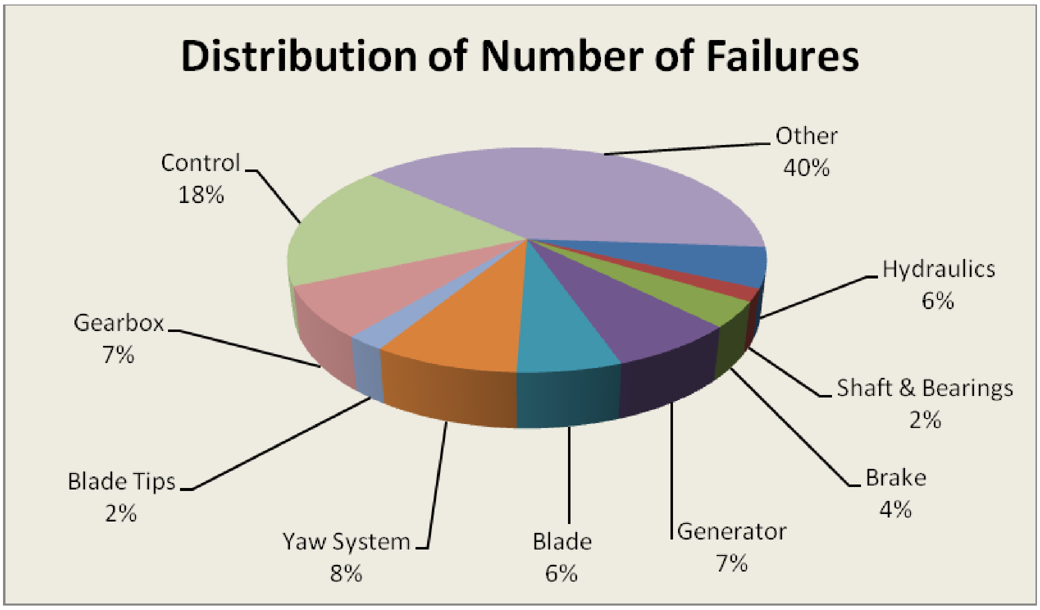


Figure E.6 Failure rates of wind turbines as percentage of total, per item, for Denmark case-study.[46,50,81,70,71]

E.1.4 Comparison of Case-Studies

A summary of the failure rates from the databases assessed for each case-study analysed in the previous paragraphs is presented in Figure E.7. German case study is experiencing higher failure rates than both the Swedish and Danish case-studies. It can be calculated from the results in Figure E.7 that the average failure rates of onshore wind turbines from the three case-studies are between 1.16 and 1.54 per year. If we only take the highest of the failure rates in Figure E.7 for Germany and Denmark that represent the majority of the wind turbines in the databases then the average value of failure rate is 1.54. If we calculate the mean of the failure rates by taking into account all the databases including the Swedish then the result is 1.16 failures per year.

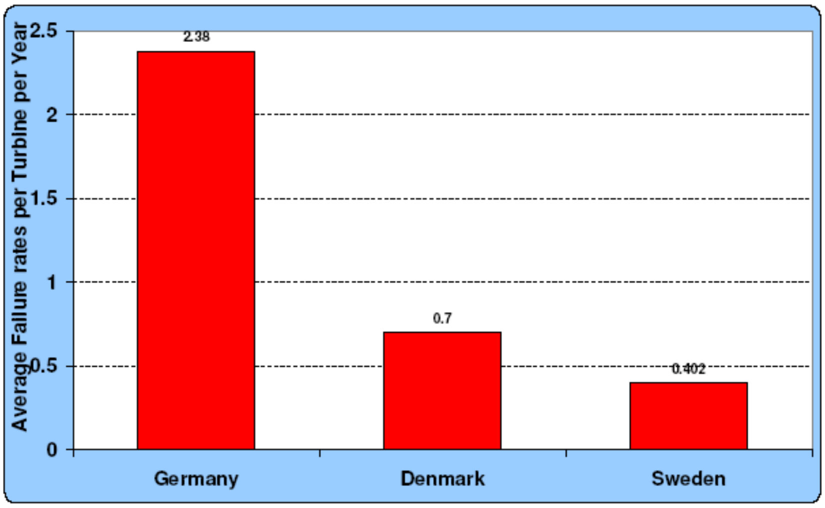


Figure E.7 Total average failure rates per turbine per year, in comparison of Germany, Denmark and Sweden.

However, Figure E.8 shows that the failure rates in Germany are falling gradually over the years and tends to reach the levels of what Denmark has experienced the last years. By comparing the slopes of the two failure rate lines for Germany and Denmark it could be observed that the failure rates of German wind turbines improve faster than the Danish, so it can be understood that significant amount of wind turbines operate still in the 'early failure' stage where the faults are higher.[46,50,81,79] Furthermore, it is found that German failure rates could fall to similar levels to Danish wind turbines within a short period of time.

Considering the analysis of the failure rates of the individual items of onshore wind turbines operating in all three countries on study, it can be observed that a specific pattern exists. Figure E.9 summarises all the findings so far for the three case-studies, where it can be observed that the electrical system and power control unit contribute the highest percentage of failures when compared to the other items, despite the fact that each database assessed differs in terms of source of data, size of wind turbine, age and method of data collection and report.

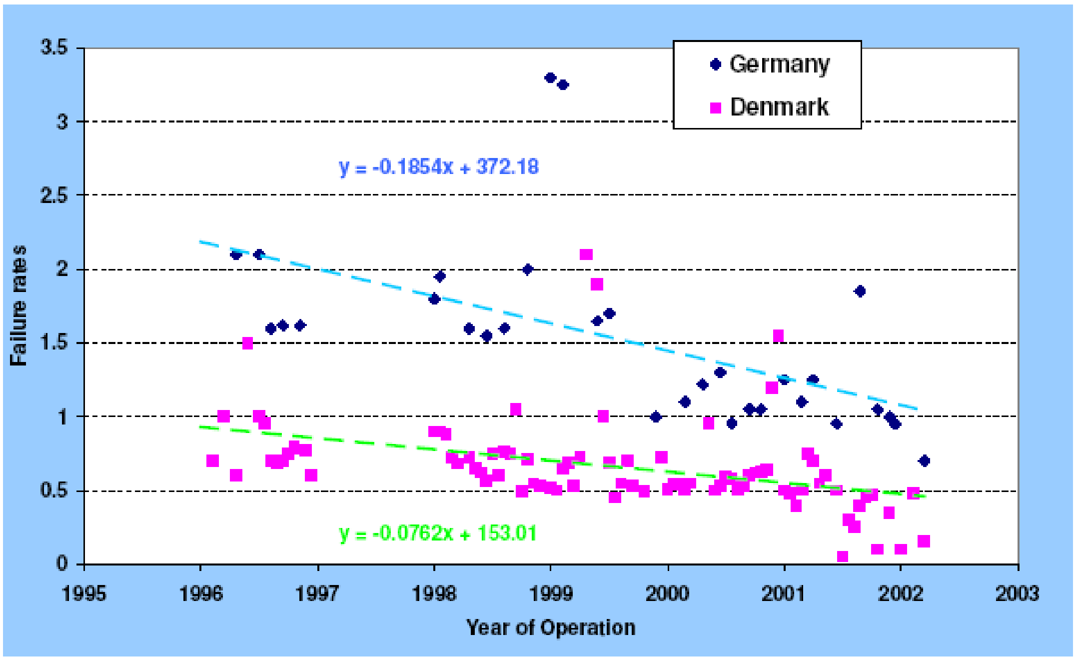


Figure E.8 Turbine failure rates for two sets of data from turbines in Denmark and Germany. [46,50,81]

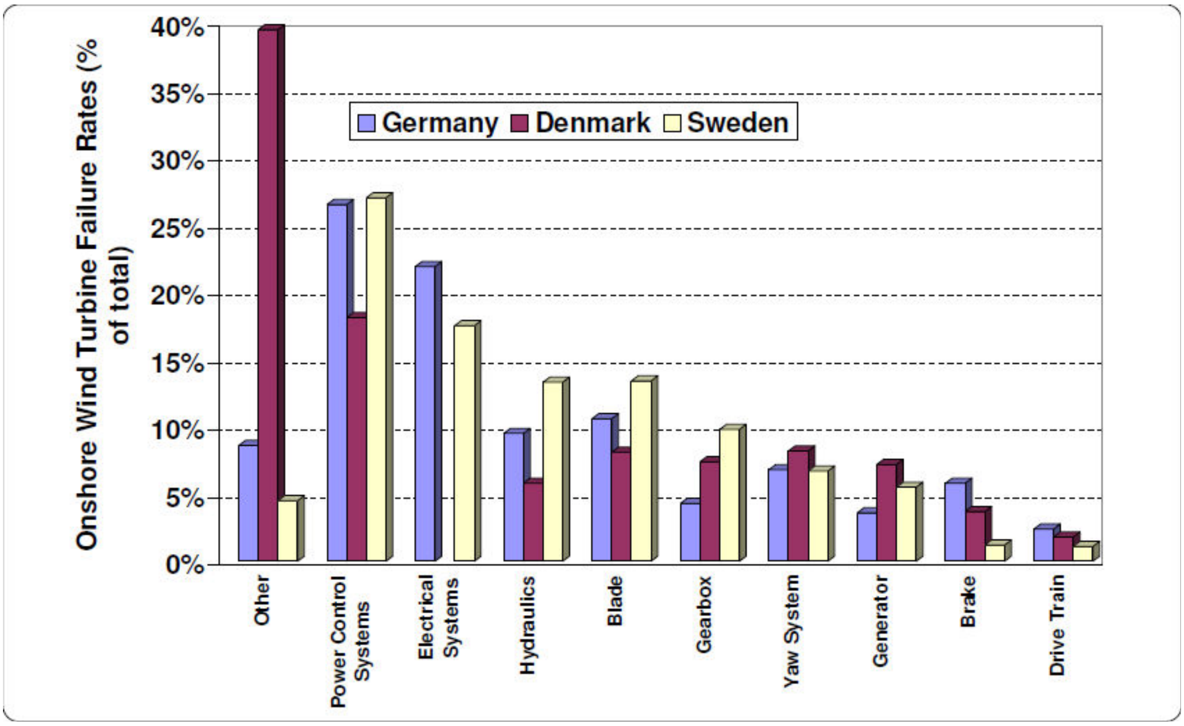


Figure E.9 Failure rates as percentage of total for all wind turbine items, for the three case-studies assessed; Germany, Denmark and Sweden.

Considering the definitions and equations of reliability of wind turbine systems, as detailed in Chapters 3 and 4, the availability of a wind turbine depends not only on the failure rates but also the mean downtime due to failures. Figure E.10 shows the mean downtime of onshore wind turbines per item as analysed by the assessment of the acquired part of the WMEP database. It can be seen in Figure E.10 that the gearbox and generator have the highest downtime among the components, but the fact that they show low failure rates, as seen in Figure E.9, results in higher availability levels, as compared to the other components.

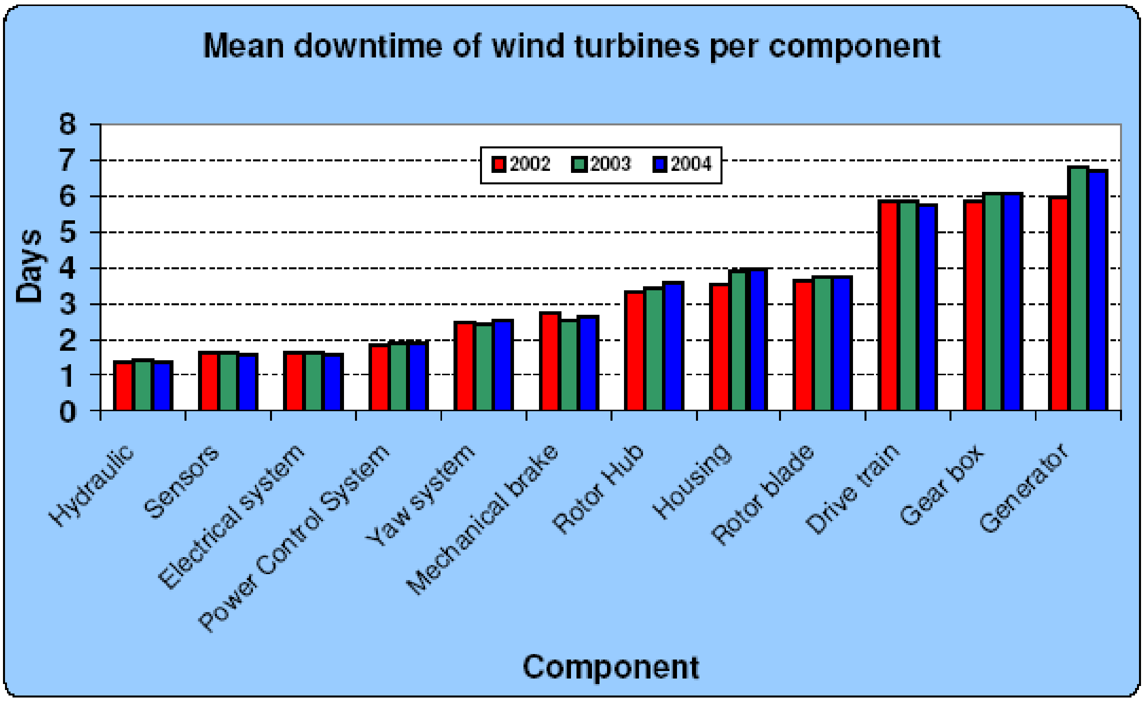


Figure E.10 Mean downtime of wind turbines in days per component. Years 2005 and 2006 show similar trends.[79]

However, if these results are transferred to the offshore wind farms, then the availability levels will be significantly different, due to weather dependency, distance to shore, marine environment and difficult accessibility, as compared to onshore wind farms. In order to explain further the above observations, an example is used for the wind turbine electrical system. This component shows high failure rates but its downtime is very low, it takes between 1 and 1.5 days to repair or replace, as seen in Figure E.10. But when this wind turbine is transferred to the offshore environment this downtime will increase considerably, leading to fundamentally reduced availability levels when the offshore wind farms are concerned. In addition to the above observations, the failure rates will also be different for the offshore wind turbines.

E.2 Wind Turbine Reliability Databases

The figures presented in this Appendix give further details of the onshore wind turbine failure fates from the different reliability databases, i.e. the WindStats, the LWK and the WMEP that were used in Chapter 4 for the development of the reliability model of the planned intervention maintenance policy O&M model.

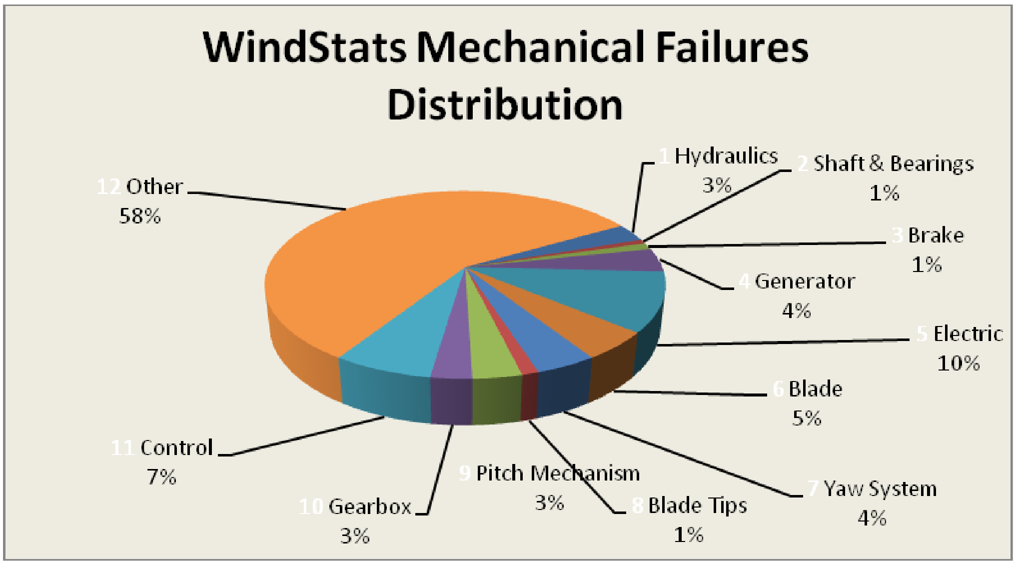


Figure E.11 Mechanical failure rates distribution according to WindStats newsletter 1999-2001, graphs drawn based on data retrieved from 46,50,81, 79

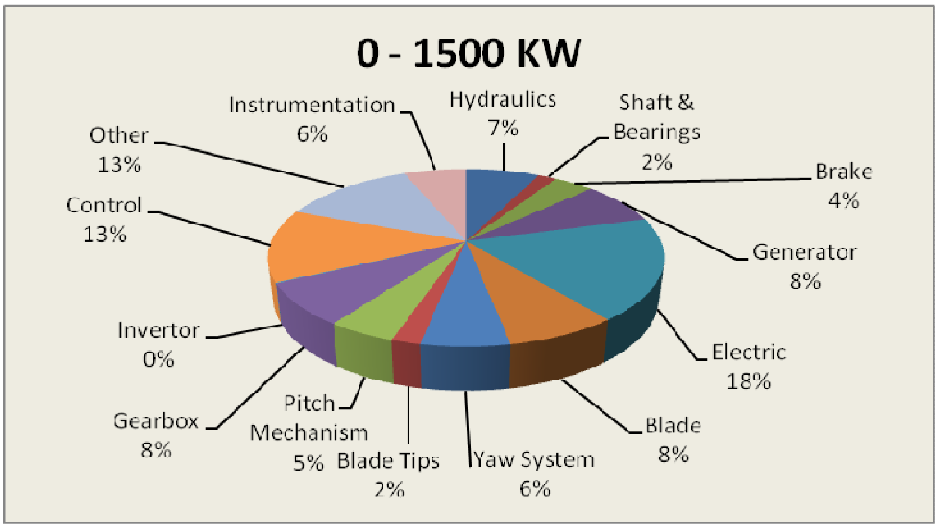


Figure E.12 Mechanical failure rates distribution according to LWK database 1999-2000, graphs drawn based on data retrieved from 46,50,81, 79

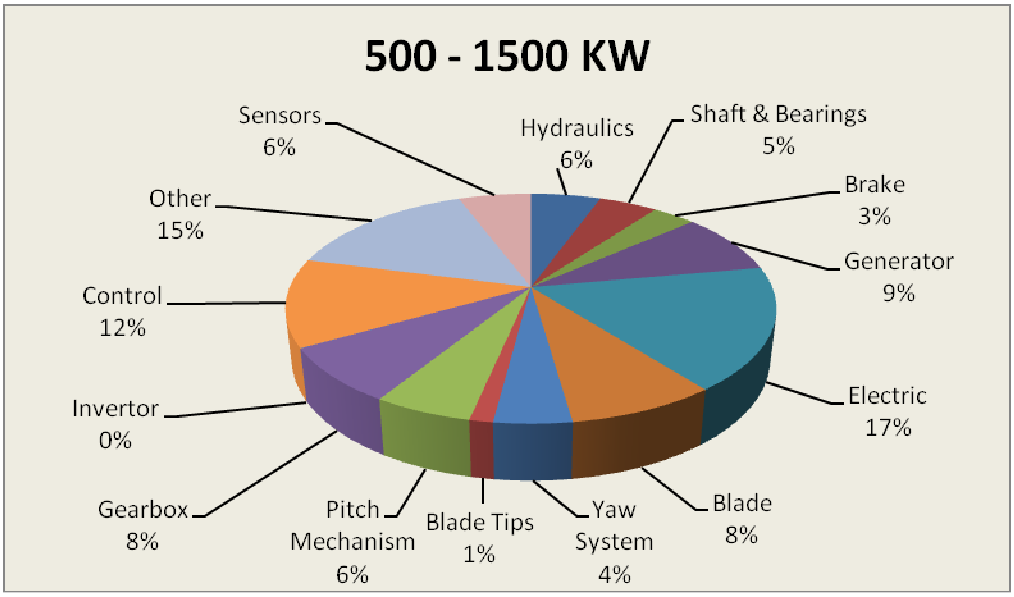


Figure E.13 Mechanical failure rates distribution according to LWK database 1999-2000, graphs drawn based on data retrieved from 46,50,81, 79

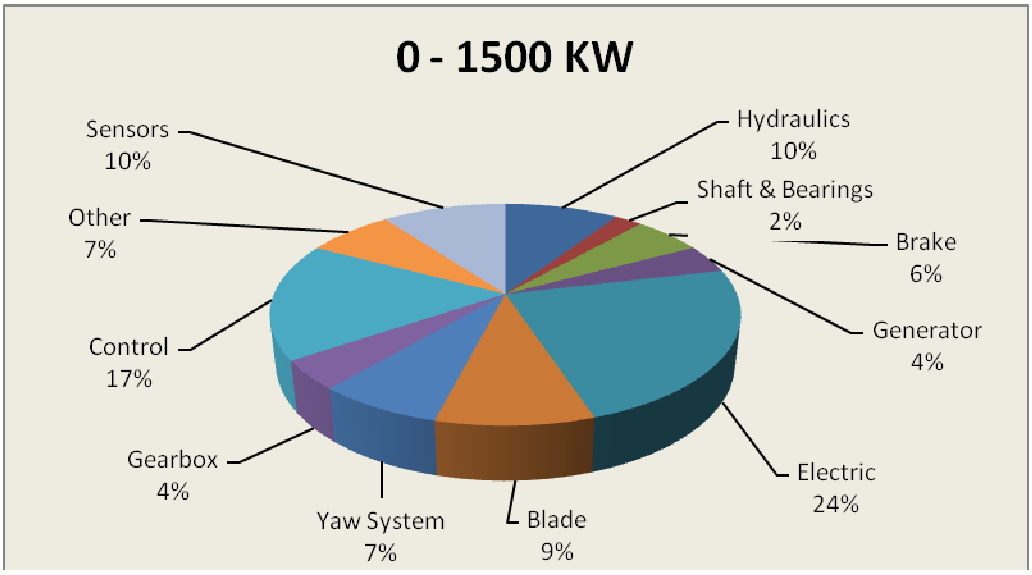


Figure E.14 Mechanical failure rates distribution according to WMEP 1998-2006, graphs drawn based on data retrieved from 46,50,81, 79

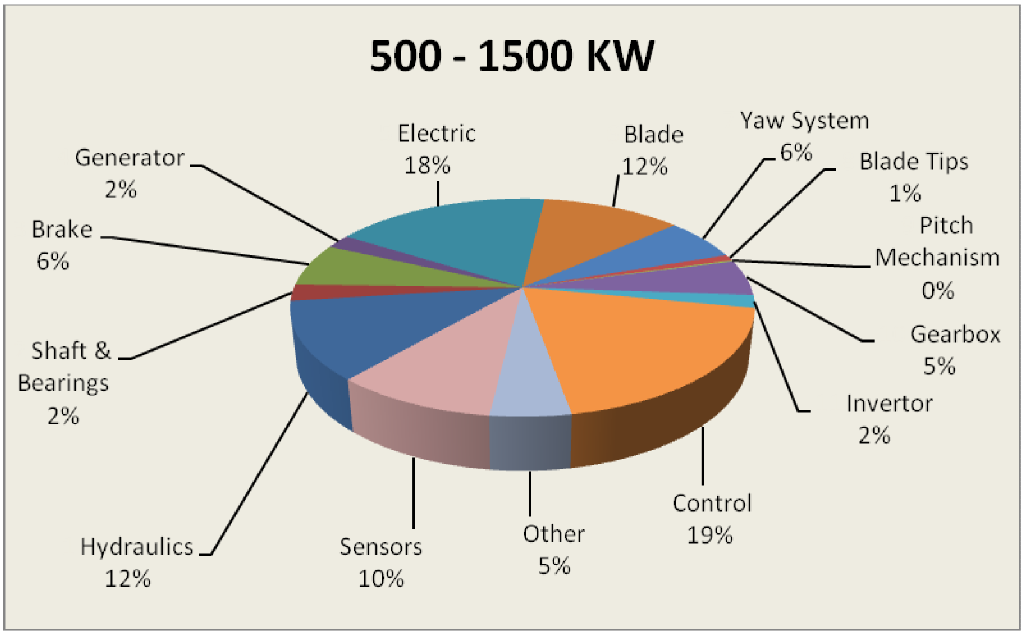


Figure E.15 Mechanical failure rates distribution according to WMEP 1998-2000, graphs drawn based on data retrieved from 46,50,81, 79

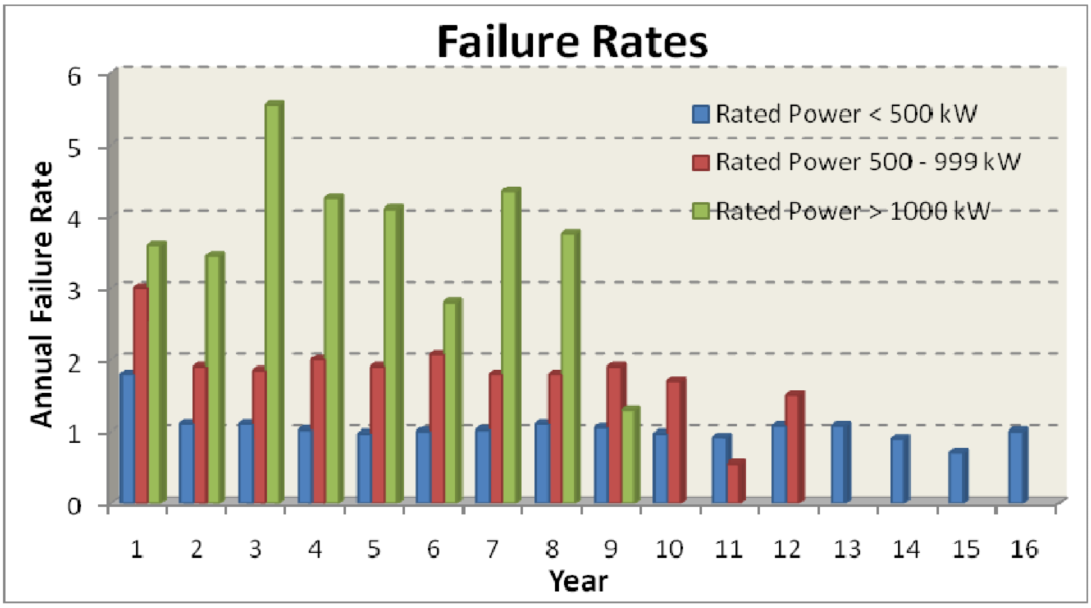


Figure E.16 Failure Rates of Wind Turbines Categorized by Rated Power, graph drawn based on data retrieved from 46,50,81, 79

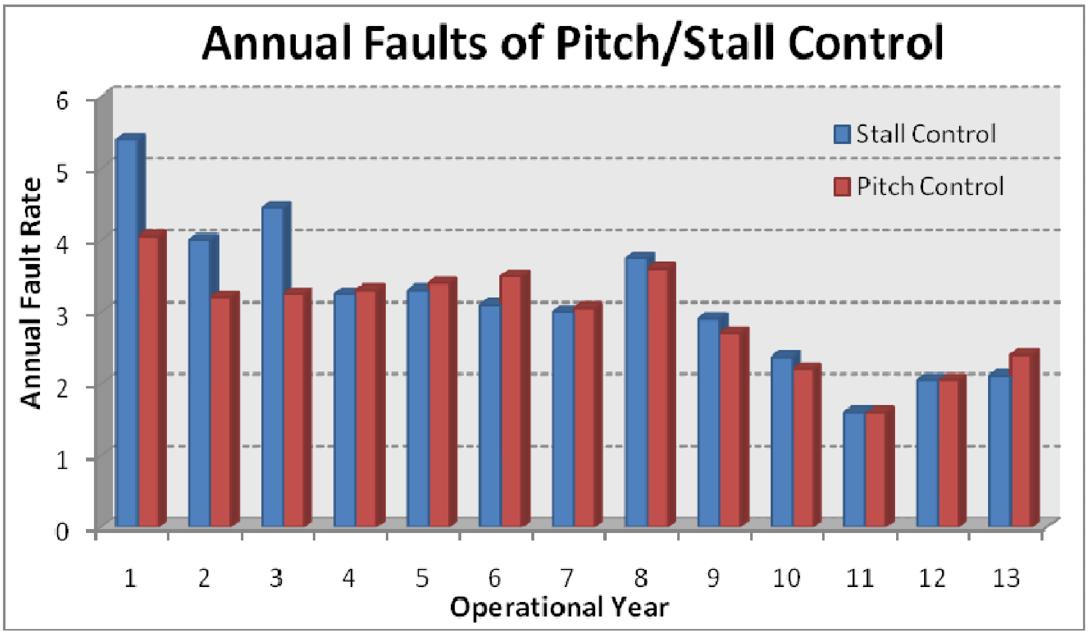


Figure E.17 Annual Faults of all Components, graph drawn based on data retrieved from 46,50,81, 79

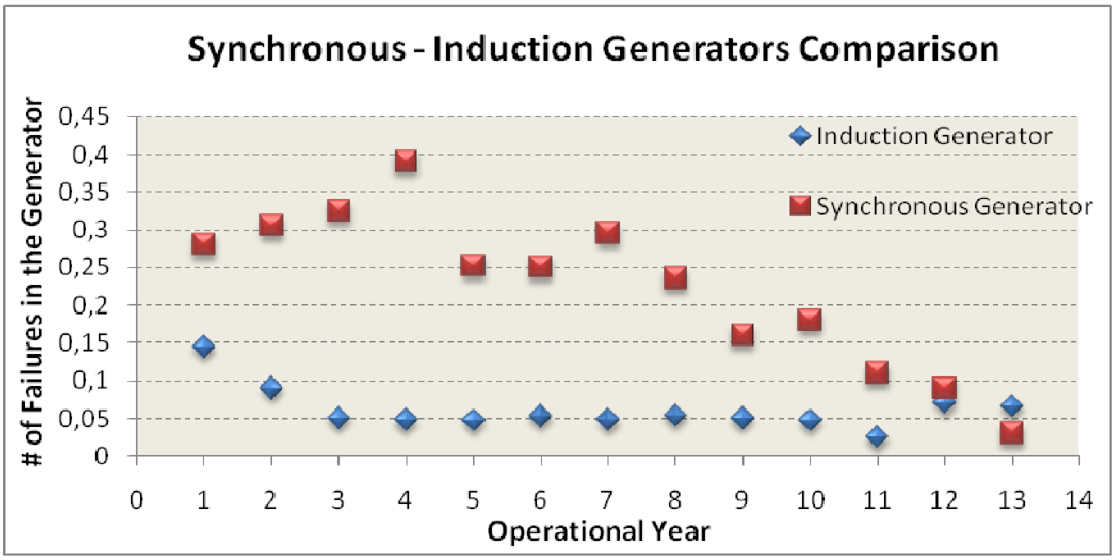


Figure E.18 Annual Faults of the Generators: comparison between synchronous and induction generators, graph drawn based on data retrieved from 46,50,81, 79

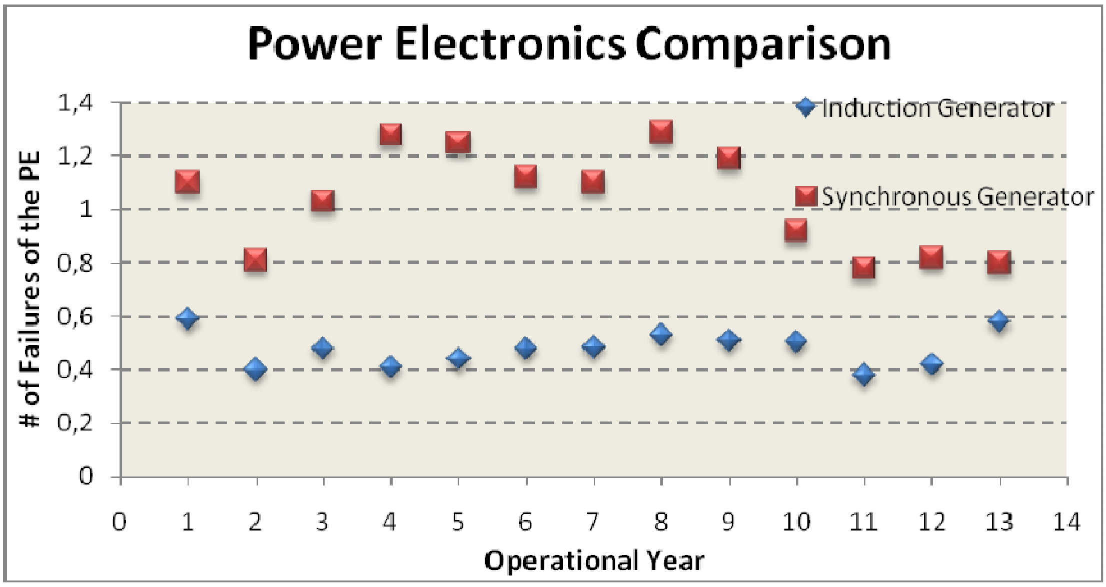


Figure E.19 Annual Faults of Power Electronic Components, comparing synchronous and induction generators, graph drawn based on data retrieved from 46,50,81, 79

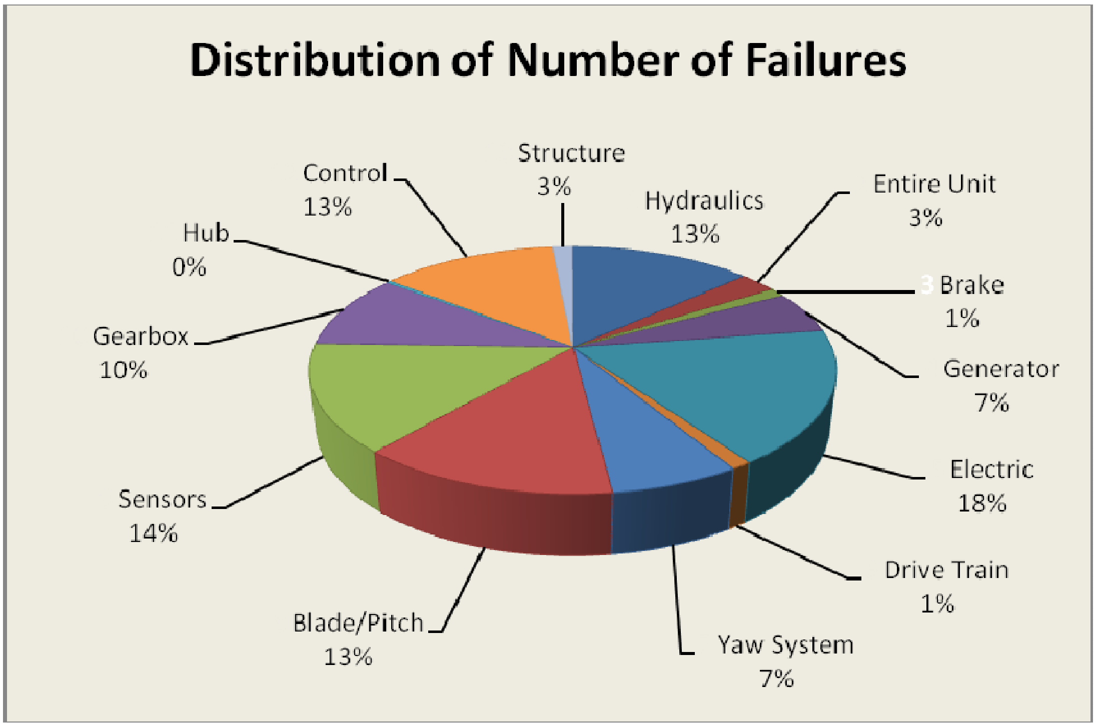


Figure E.20 Distribution of number of failures for Swedish wind power plants 2000 – 2004, graph drawn based on data retrieved from 80,156,157

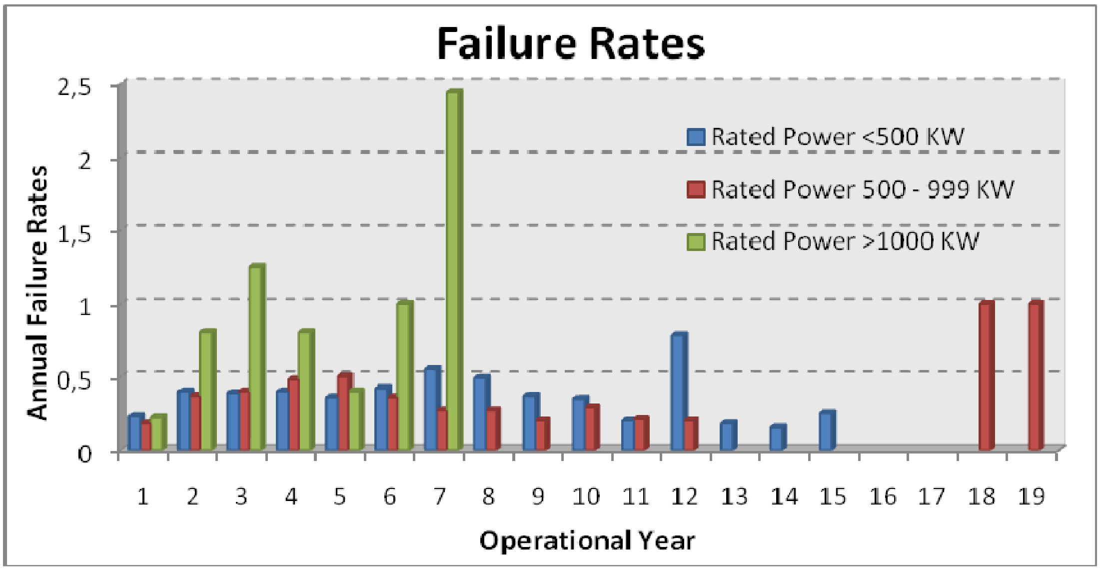


Figure E.21 Failure Rates of Wind Turbines Categorized by Rated Power, Graph drawn based on data retrieved from 80,156,157

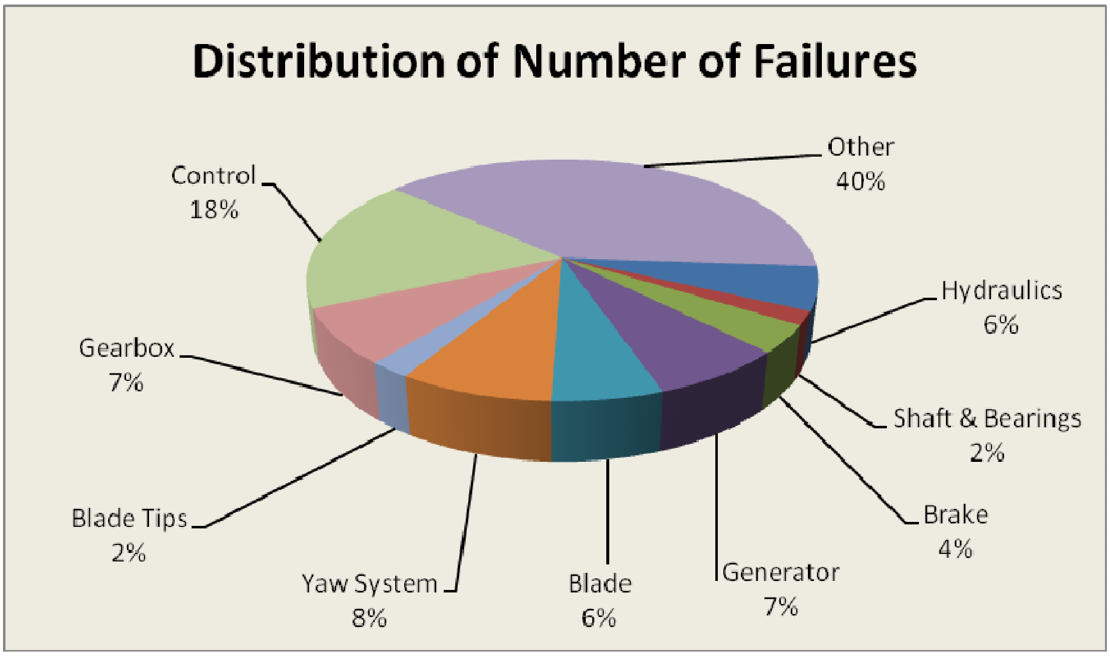


Figure E.22 Mechanical failure rates distribution according to WindStats 1999 - 2001, graph drawn based on data retrieved from 46,50,81, 79

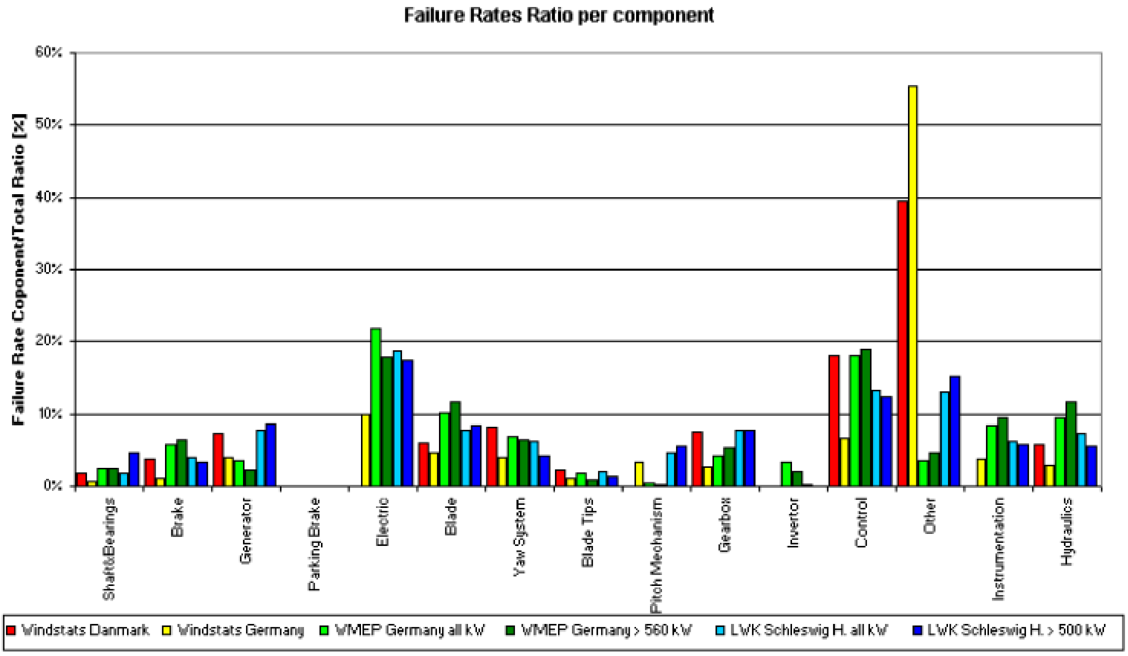


Figure E.23 Failure rates of wind turbines per component from the DOWEC project.[70,71]

E.3 Tables for Wind Turbine Failure rates from the Databases

The Tables presented in this Appendix give a tabular presentation of the failure rates of onshore wind turbines from the different databases used in Chapter 4 and Appendices E.1 and E.2 for the development of the reliability model of offshore wind turbines.

LWK Schleswig-Holstein failure rates [1/year]		1999		2000	
		0-1500 kW	500-1500 kW	0-1500 kW	500-1500 kW
	Avg reported turbines:	543	288	480	298
LWK components	**Report components**				
Rotorblade	Blade	0.140	0.198	0.123	0.124
Rotorbrake	Blade tip	0.028	0.017	0.040	0.034
Pitch Adjustment	Pitch mechanism	0.085	0.122	0.075	0.091
Mech. Brake	Brake	0.037	0.038	0.096	0.094
Main shaft/bearing	Shaft & Bearing	0.026	0.139	0.035	0.040
Gearbox	Gear box	0.112	0.135	0.154	0.168
Generator	Generator	0.122	0.163	0.146	0.171
Hydraulics	Hydraulics	0.105	0.076	0.144	0.138
Yaw System	Yaw System	0.103	0.073	0.106	0.094
Windvane/anemometer	Instrumentation	0.039	0.038	0.046	0.050
Elec. Controls	Control	0.219	0.229	0.238	0.252
Elec. System	Electric	0.335	0.368	0.306	0.305
Convertor	Invertor	0.002	0.000	0.002	0.000
Sensors	Instrumentation	0.068	0.080	0.056	0.054
Other	Other	0.221	0.337	0.227	0.255
	Total:	1.641	2.014	1.794	1.869

Figure E.24 Failure rates of wind turbines per component categorized in power classes from the LWK Schleswig-Holstein database. [70,71]

Denmark failure rates per year according to Windstats Newsletter										
		3rd quarter '99	4th quarter '99	1st quarter '00	2nd quarter '00	3rd quarter '00	4th quarter '00	1st quarter '01	2nd quarter '01	Average
	Avg reported turbines:	2032.3	1961.7	1942.0	1793.3	2111.0	2111.0	2073.0	1896.7	1990.1
Windstats compone	**Report components**									
Blades	Blade	0.045	0.061	0.047	0.029	0.023	0.036	0.037	0.036	0.04
Hub	Blade	0.002	0.000	0.008	0.000	0.000	0.000	0.002	0.002	0.00
Axle/Bearing	Shaft & Bearin	0.010	0.014	0.016	0.011	0.004	0.008	0.004	0.013	0.01
Air brake	Blade tip	0.012	0.031	0.019	0.011	0.008	0.015	0.012	0.017	0.02
Gearbox	Gearbox	0.045	0.049	0.076	0.036	0.042	0.042	0.075	0.046	0.05
Coupling	Shaft & Bearin	0.004	0.006	0.004	0.002	0.002	0.000	0.000	0.004	0.00
Brakes	Brake	0.020	0.047	0.047	0.018	0.015	0.017	0.015	0.023	0.03
Generator	Generator	0.045	0.053	0.074	0.036	0.042	0.055	0.066	0.030	0.05
Yaw system	Yaw system	0.045	0.077	0.091	0.051	0.045	0.044	0.050	0.051	0.06
Tower	Other	0.004	0.008	0.004	0.000	0.006	0.000	0.000	0.000	0.00
Foundation	Other	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00
Grid (is left out)	--	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.015	0.01
Elec. Control	Control	0.102	0.167	0.165	0.145	0.133	0.117	0.096	0.074	0.12
Mech. Control	Other	0.004	0.027	0.010	0.009	0.011	0.011	0.012	0.002	0.01
Hydraulic	Hydraulics	0.037	0.061	0.056	0.018	0.047	0.038	0.027	0.034	0.04
Entire nacelle	Other	0.008	0.016	0.008	0.002	0.000	0.000	0.006	0.002	0.01
Entire turbine	Other	0.018	0.163	0.122	0.022	0.019	0.027	0.021	0.057	0.06
Other	Other	0.159	0.290	0.301	0.132	0.165	0.155	0.224	0.158	0.20
	Total:	0.563	1.071	1.048	0.522	0.561	0.565	0.679	0.563	0.70

Germany failure rates per year according to Windstats Newsletter										Average excl.
		3rd quarter '99	4th quarter '99	1st quarter '00	2nd quarter '00	3rd quarter '00	4th quarter '00	1st quarter '01	2nd quarter '01	3rd quarter '99
	Avg reported turbines:	2516.7	2766.3	2553.0	2611.3	2895.7	3032.3	2798.7	3017.7	2810.7
Windstats compone	**Report components**									
Non-component assoc	Other	0.670	0.159	0.154	0.163	0.162	0.107	0.102	0.093	0.13
Rotor	Blade	0.730	0.132	0.142	0.094	0.080	0.065	0.077	0.061	0.09
Air brake	Blade tip	0.148	0.037	0.028	0.035	0.025	0.025	0.019	0.013	0.03
Mech. Brake	Brake	0.150	0.024	0.025	0.033	0.022	0.034	0.022	0.021	0.03
Pitch Adjustment	Pitch mechanis	0.432	0.102	0.093	0.099	0.044	0.069	0.057	0.049	0.07
Main shaft/bearing	Shaft & Bearin	0.087	0.009	0.031	0.024	0.011	0.022	0.017	0.015	0.02
Gearbox	Gearbox	0.215	0.082	0.107	0.087	0.052	0.096	0.109	0.061	0.08
Generator	Generator	0.476	0.146	0.163	0.079	0.048	0.090	0.093	0.064	0.10
Yaw System	Yaw system	0.532	0.083	0.098	0.123	0.104	0.046	0.078	0.104	0.09
Windvane/anemomete	Instrumentatior	0.174	0.037	0.048	0.033	0.019	0.024	0.045	0.021	0.03
Elec. Controls	Control	0.839	0.174	0.233	0.178	0.107	0.161	0.160	0.067	0.15
Elec. System	Electric	1.212	0.333	0.260	0.277	0.191	0.203	0.264	0.166	0.24
Hydraulics	Hydraulics	0.301	0.067	0.107	0.081	0.080	0.080	0.091	0.064	0.08
Sensors	Instrumentatior	0.328	0.096	0.079	0.044	0.019	0.037	0.042	0.043	0.05
Other components	Other	0.353	0.060	0.076	0.071	0.051	0.056	0.038	0.033	0.06
Only failure reported	Other	1.466	1.201	1.442	1.511	1.577	1.850	2.345	2.552	1.78
	Total:	8.113	2.744	3.087	2.933	2.590	2.968	3.557	3.428	3.04

Figure E.25 Denmark and Germany wind turbine failure rates according to Windstats database.[70,71]

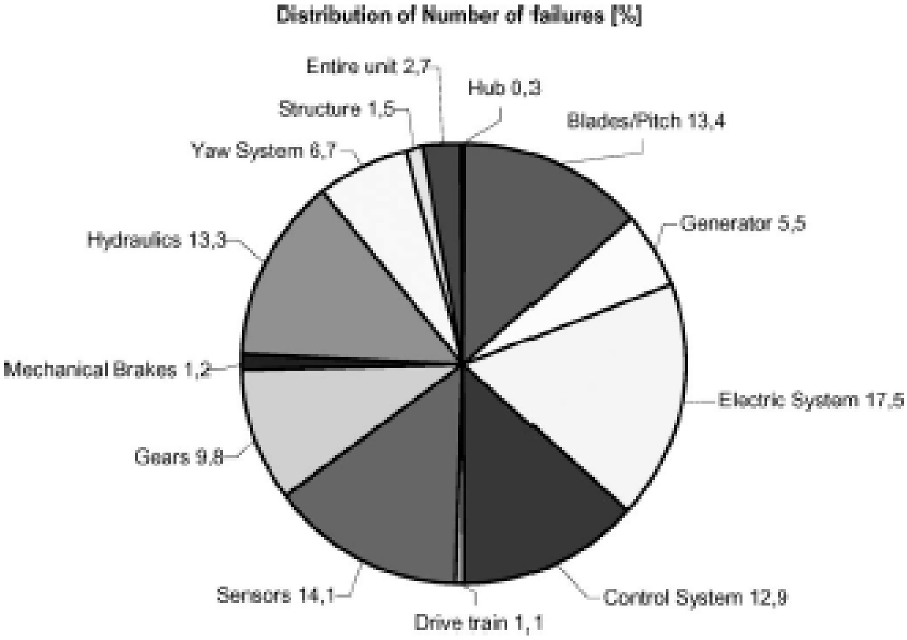


Fig. 1. Distribution of number of failures for Swedish wind power plants between 2000–2004.

Figure E.26 Distribution of failures from wind turbines for Sweden between 2000 and 2004.[80,156,157]

DOWNTIMES AND FAILURE FREQUENCIES FOR COMPONENTS IN SWEDISH WIND POWER PLANTS 2000–2004

Component	Entire unit	Structure	Yaw system	Hydraulics	Mechanical brakes	Gears	Sensors	Drive train	Control system	Electric system	Generator	Blades/Pitch	Hub	Total
Total downtime per component, 2000-2004 (hours)	2631	1874	20754	6918	1881	30286	8357	3788	28620	22395	13906	14743	50	156202
Average downtime per year (hours/year)	526	375	4151	1384	376	6057	1671	758	5724	4479	2781	2949	10	31240
Average downtime per year per turbine (hours)	0,8	0,6	6,6	2,6	0,6	11,6	2,7	1,2	9,2	7,2	4,5	4,7	0,0	52,4
Distribution of downtime, 2000-2004 (%) (see Fig. 2)	1,7	1,2	13,3	4,4	1,2	19,4	5,4	2,4	18,3	14,3	8,9	9,4	0,0	100,0
Total number of failures per component, 2000-2004	33	18	80	160	15	118	169	13	155	210	66	161	4	1202
Average number of failures per year	6,6	3,6	16,0	32,0	3,0	23,6	33,8	2,6	31,0	42,0	13,2	32,2	0,8	240,4
Average number of failures per year per turbine	0,011	0,006	0,026	0,061	0,005	0,045	0,054	0,004	0,050	0,067	0,021	0,052	0,001	0,402
Distribution of failures, 2000 -2004 (%) (see Fig. 1)	2,7	1,5	6,7	13,3	1,2	9,8	14,1	1,1	12,9	17,5	5,5	13,4	0,3	100,0
Average downtime per failure, 2000-2004 (hours)	79,7	104,1	259,4	43,2	125,4	256,7	49,4	291,4	184,6	106,6	210,7	91,6	12,5	130,0

Figure E.27 The downtime and failure frequencies for different wind turbine components for the Sweden wind power plants between 2000 and 2004.[80,156,157]

F. Analytical solutions

In order to support and validate the accuracy of the results obtain through the use of Monte Carlo simulations, analytical solutions for the mean availability and the standard deviation of the first year of the O&M model for the planned intervention maintenance policy have been developed.[158] The mean of a random variable is a measure of the central tendency of the distribution. Hence, the mean availability for the first year (A_1) of the wind farm operation can be calculated by considering the availability equations given in Chapter 4 for the development of the Monte Carlo model:[5]

$$A_1 = \int_0^1 t\, f(t)\, dt \;+\; \int_1^\infty f(t)\, dt \qquad \text{F.1}$$

Where f(t) is the density function of the exponential distribution with mean time to failure "μ":[5]

$$f(t) = \frac{1}{\mu} e^{-t/\mu} \qquad \text{F.2}$$

From Equations F.1 and F.2 we get that:

$$A_1 = \mu (1 - e^{-1/\mu}) \qquad \text{F.3}$$

Equation F.4 presents a generalised of the wind farm availability between the different years, by taking into consideration that A_n is the availability of the last year of operation, while assuming that the wind turbines are repaired once a year and there is no preventive maintenance applied.

$$A_n = A_{n-1} \qquad \text{F.4}$$

Considering equations F.3 and F.4 then the following expressions represent the wind farm availability for A_n and A_{n-1}:

Where $A_n = \int_{n-1}^{n} (t-n+1) f(t)dt + \int_{n}^{\infty} f(t)dt + \left\{ \int_{0}^{n-1} tf(t)dt + \int_{n-1}^{\infty} f(t)dt \right\} \bullet \int_{0}^{n-1} f(t)dt$ and

$$A_{n-1} = \int_{n-2}^{n-1} (t-n+2) f(t)dt + \int_{n}^{\infty} f(t)dt + \left\{ \int_{0}^{n-2} tf(t)dt + \int_{n-2}^{\infty} f(t)dt \right\} \bullet \int_{0}^{n-2} f(t)dt$$

The next step was to analytically calculate the standard deviation of the distribution. The variance or standard deviation is the measure of dispersion in the distribution. If a random variable has a large variance, then an observed value of the random variable is more likely to be far from the mean μ.[6] Hence the mean square availability is:[158]

$$E\left[t^2\right] = \int_0^1 t^2 f(t)\, dt + \int_1^{\infty} f(t)\, dt \qquad \text{or}$$

$$E\left[t^2\right] = 2\mu^2 - 2\mu^2 e^{-1/\mu} - 2\mu\, e^{-1/\mu} \tag{F.6}$$

By using Equations F.3 and F.6 the variance of availability σ_1 is calculated:[158]

$$\sigma_1^2 = E[t^2] - A_1^2 \qquad \text{or}$$

$$\sigma_1 = (\mu^2 - \mu^2 e^{-2/\mu} - 2\mu\, e^{-1/\mu})^{1/2} \tag{F.7}$$

When applying specific numbers to the above equations, it could be verified that the results will match the simulation results from the O&M models developed.

G.1 O&M model histograms and accuracy of output results

The histograms presented in this Appendix give an example of the variability of the mean wind farm availability of the O&M model that is achieved when using the Monte Carlo method. These figures show an example of a trial and error test for the accuracy of results, as described in Chapter 4, which is required for every case study that the O&M model of the planned intervention maintenance policy is simulated. The y-axis of the histograms give the frequency of occurrence of the output parameter and the x-axis gives the actual value of the output parameter, e.g. wind farm availability. The frequency of occurrence represents the number of simulations, i.e. the number of Monte Carlo iterations used for the simulation of the model, while the x-axis gives the actual value of the wind farm availability. The red line on the histograms represents how a normal distribution should fit on the data. The skewness and kurtosis of a normal distribution should be zero and 3 respectively, as detailed in the Definitions section of this thesis, while the calculated skewness and kurtosis of the simulated distribution is presented in tabulated form on the side of each histogram. For the O&M model to yield accurate results then the blue bars representing the output distribution from the O&M model should follow the shape, the skewness and the kurtosis of the red line, i.e. the simulated distribution should follow the Central Limit Theorem, as detailed in the Definitions section of this thesis. It can be observed from the graphs in this appendix that this is achieved for simulations above 10,000. This trial and error process to identify the number of simulations required for the O&M model is performed for every case study and every sensitivity analysis performed in this thesis.

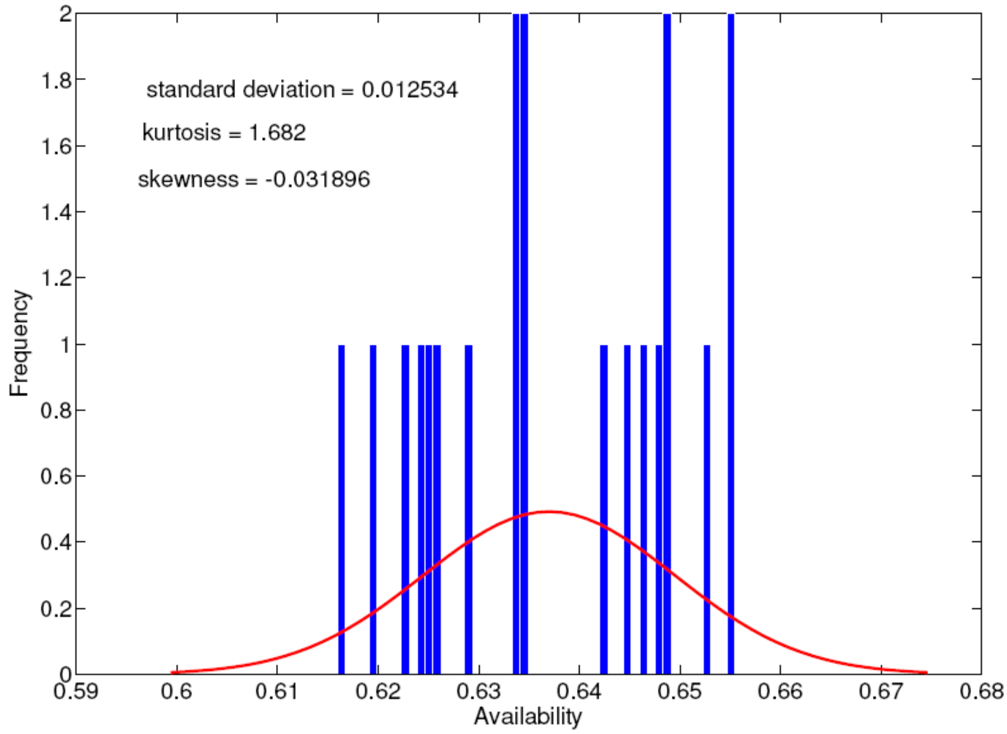


Figure G.1 The histogram of wind farm availability distribution for 20 simulations of the O&M model

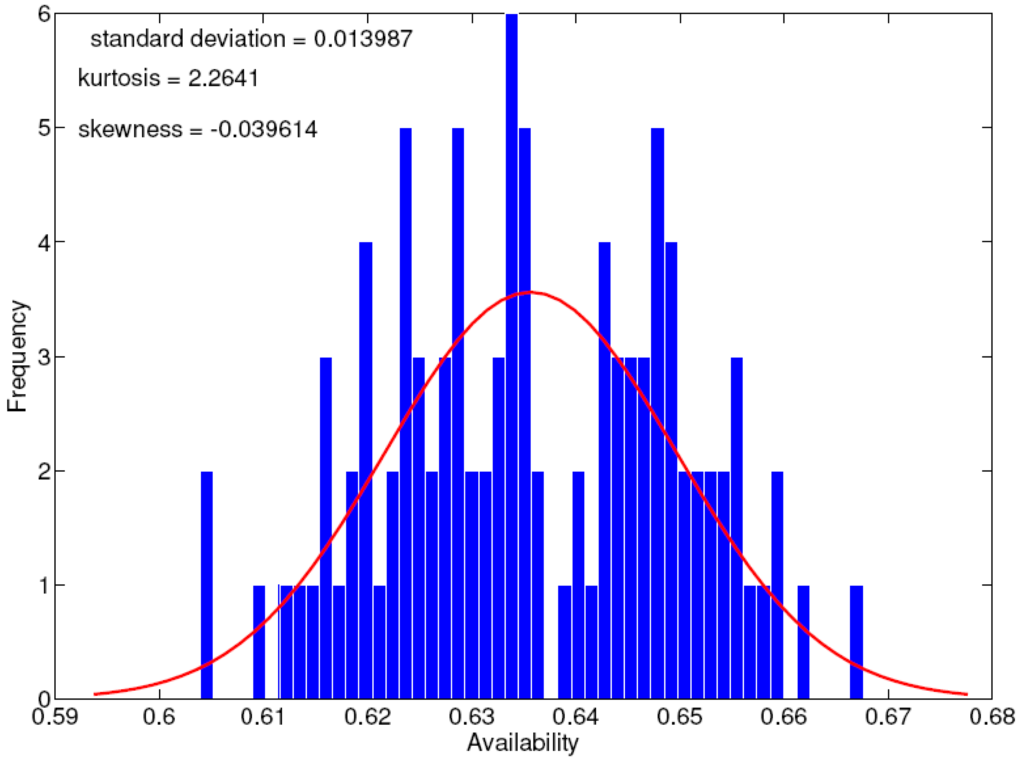


Figure G.2 The histogram of wind farm availability distribution for 100 simulations of the O&M model

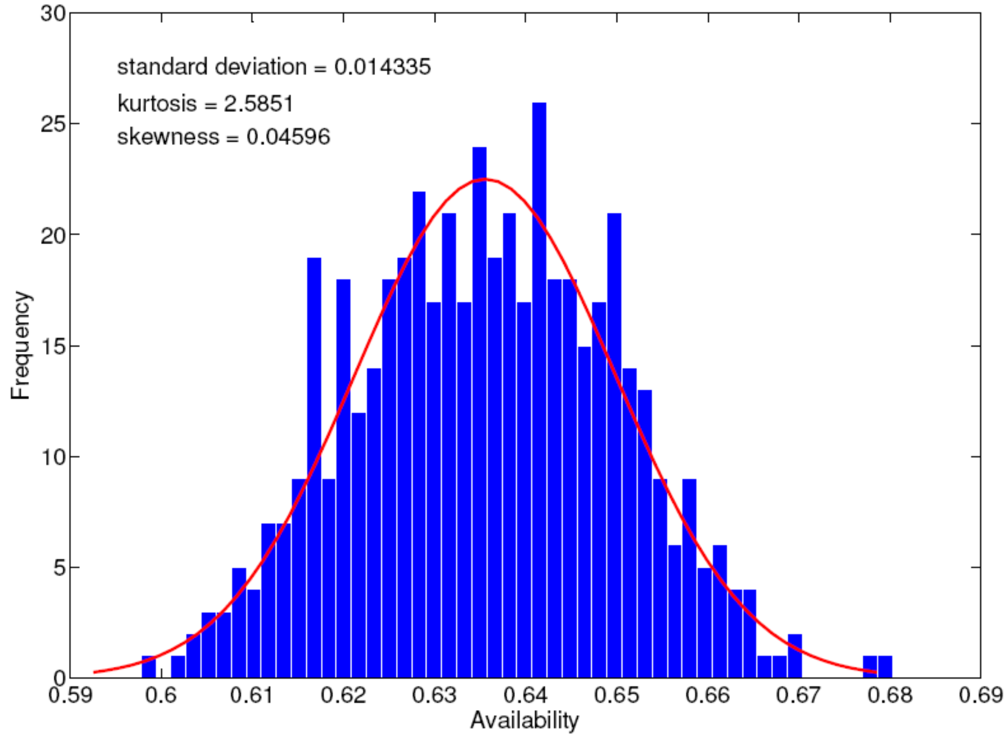


Figure G.3 The histogram of wind farm availability distribution for 500 simulations of the O&M model

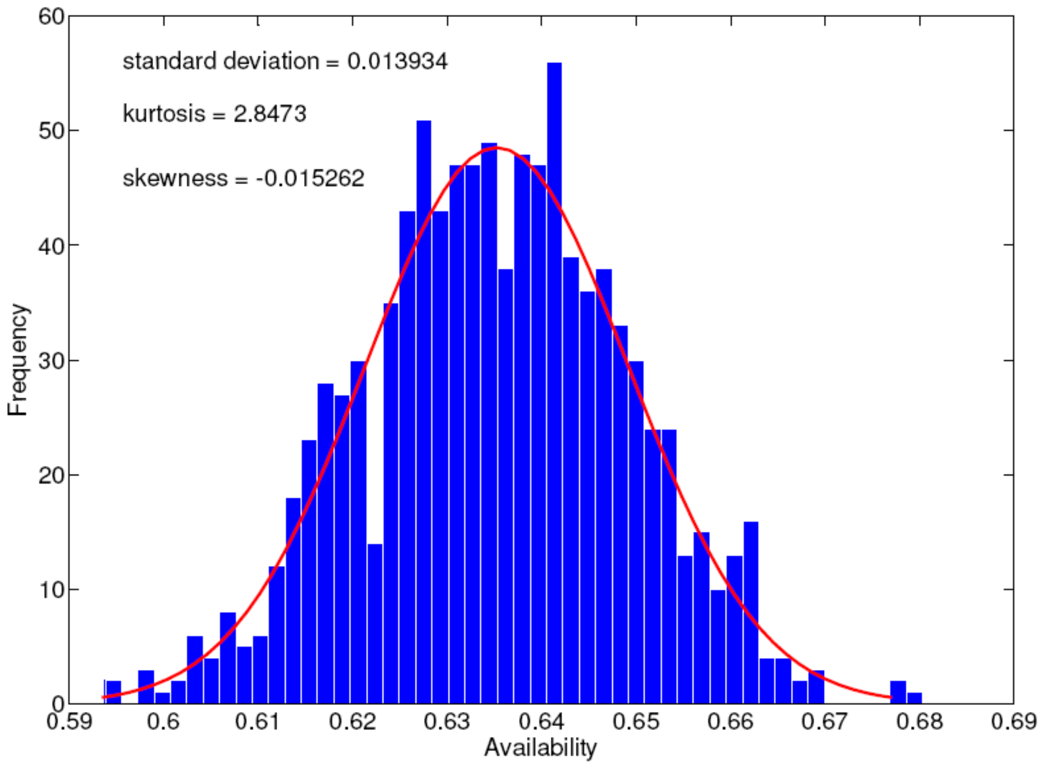


Figure G.4 The histogram of wind farm availability distribution for 1,000 simulations of the O&M model

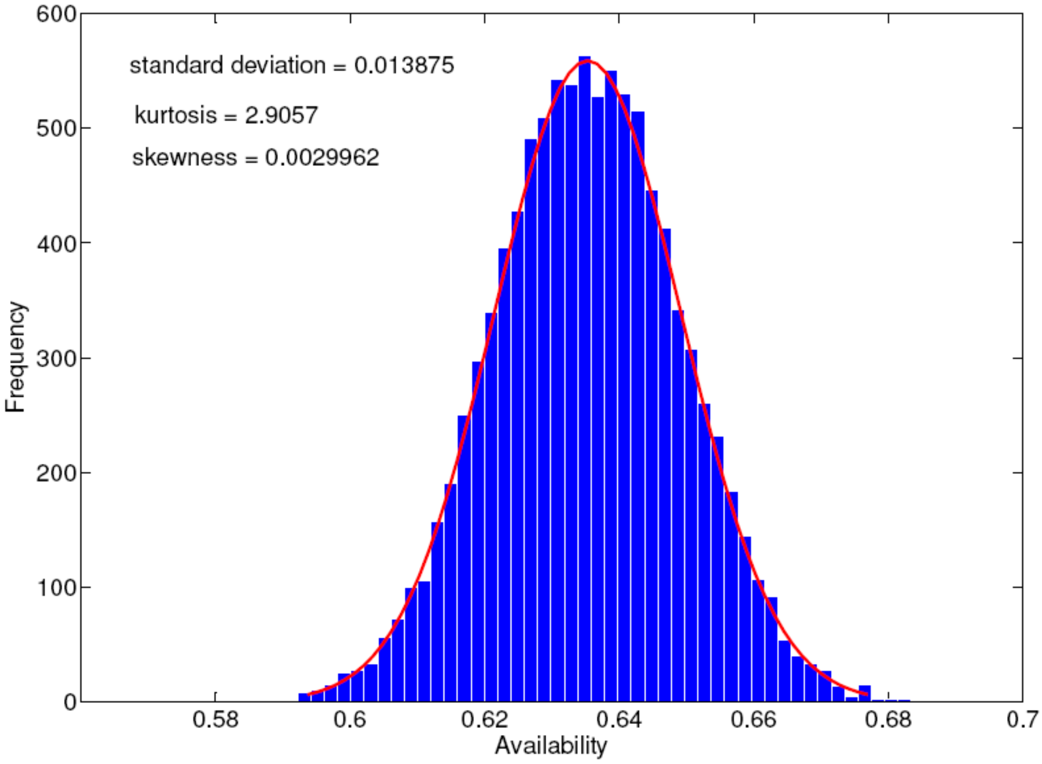


Figure G.5 The histogram of wind farm availability distribution for 10,000 simulations of the O&M model

G.2 Statistical distribution measures

G.2.1 Error Calculation

The standard error of the mean is the standard deviation of the sample mean estimate of a population mean. The standard error is estimated by the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size (assuming statistical independence of the values in the sample):[3]

$$SD = \frac{\sigma}{\sqrt{n}} \tag{G.1}$$

where σ is the standard deviation (i.e., the sample based estimate of the standard deviation of the population), and n is the size (number of observations) of the sample.

G.2.2 Skewness calculation

Skewness is a measure of the asymmetry of the data around the sample mean. If skewness is negative, the data are spread out more to the left of the mean than to the right. If skewness is positive, the data are spread out more to the right. The skewness of the normal distribution (or any perfectly symmetric distribution) is zero. The skewness of a distribution is defined as:[3]

$$y = \frac{(x-\mu)^3}{\sigma^3} \tag{G.2}$$

Where μ is the mean of x, σ is the standard deviation of x.

G.2.3 Kurtosis calculation

Kurtosis is a measure of how flat a distribution is. The kurtosis of the normal distribution is 3. Distributions that are more flat than the normal distribution have kurtosis greater than 3; distributions that are less outlier-prone have kurtosis less than 3. The kurtosis of a distribution is defined as:[3]

$$k = \frac{(x-\mu)^4}{\sigma^4} \tag{G.3}$$

Where μ is the mean of x, σ is the standard deviation of x.

G.3 Calculation of MTTF of a preventively maintained system

To calculate the MTTF (mean time to failure) of a system that is under preventive maintenance (i.e. inspection, lubrication, recalibration and adjustments) at fixed intervals then the following equation described by Kumar et al (2000) could be used:[3]

$$MTTF_{PM} = \frac{\int_0^{T_{PM}} R(t)dt}{1 - R(T_{PM})}$$

Where:

$MTTF_{PM}$	is the mean time to failure of the system that is preventively maintained.
T_{PM}	is the fixed time intervals that the system is preventively maintained.
R(t)	is the reliability of the system subject to preventive maintenance

This equation is used in the O&M model to calculate the new reliability of the wind turbines after every preventive maintenance expedition by substituting the components' MTTF with the calculated $MTTF_{PM}$ after the preventive maintenance.

G.4 Markov modelling

A different approach from the Monte Carlo method for modelling the statistical variability of input parameters of the O&M model for the planned intervention maintenance policy could be the Markov modelling, but its suitability to the needs of the planned intervention maintenance policy for offshore wind farms is found inadequate. Markov's models are used in cases where each component of the system needs to be simulated individually and the working – fail state of it affects and depends on other components too. These kinds of model have the capability of modelling dependencies between critical components in systems, which is not the aim of the planned intervention maintenance policy.[159] Since if a critical component of a wind turbine fails (or is reported malfunctioning) then the operators will stop the wind turbine waiting for maintenance to commence.

In addition to the above, the Markov method can be applied to models where the probabilities of a component changing from one state to another, i.e. working state to failed state, must remain constant. In other words, the Markov method can only be used when a constant failure rate is applied to the system.[159] That is not the immediate aim of the planned intervention maintenance policy, since the variability in the reliability levels of the wind turbines has to be taken into consideration.[159]

H. Program diagrams

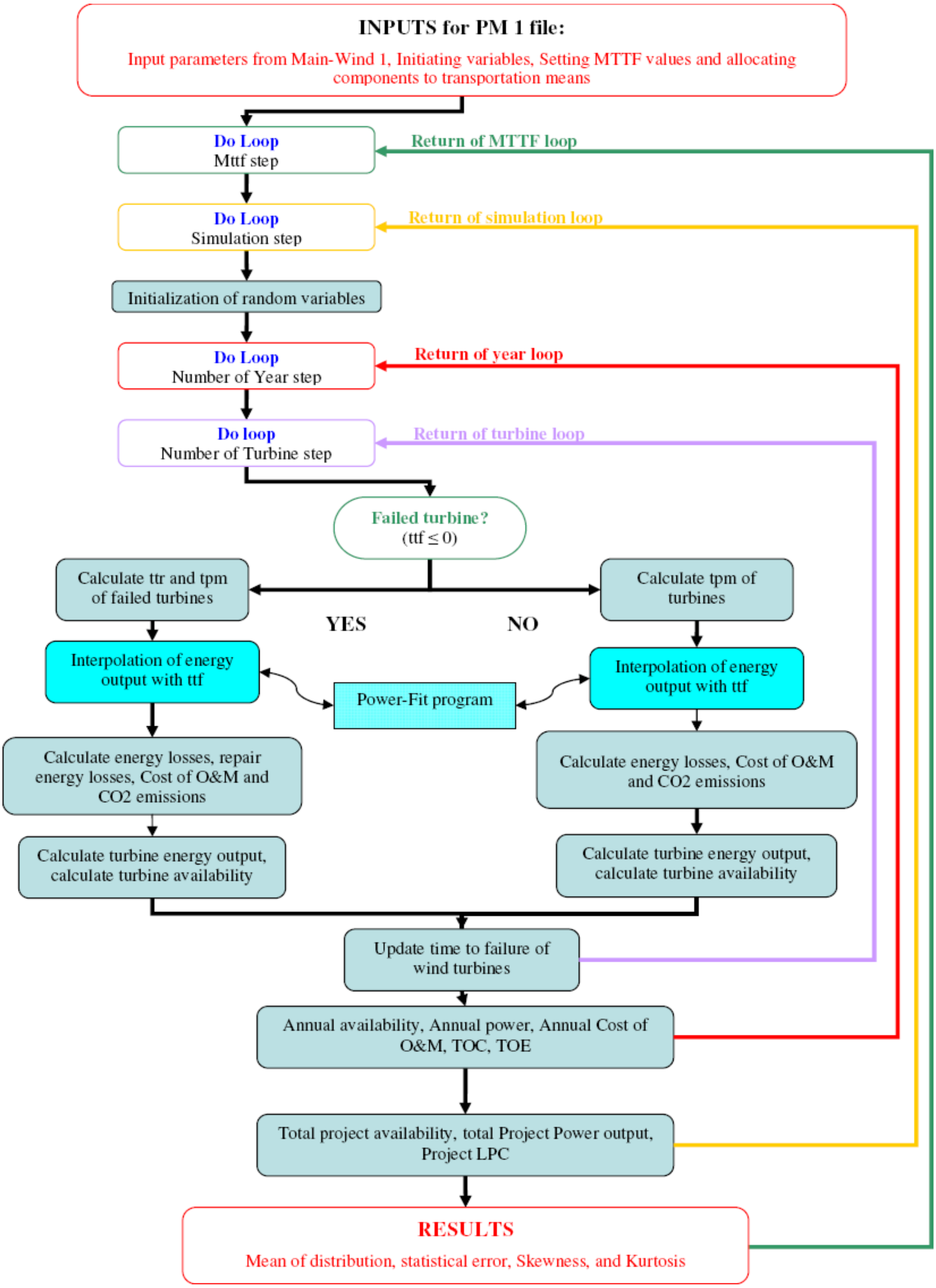


Figure H.1 The structure of Matlab® code for PM 1 program

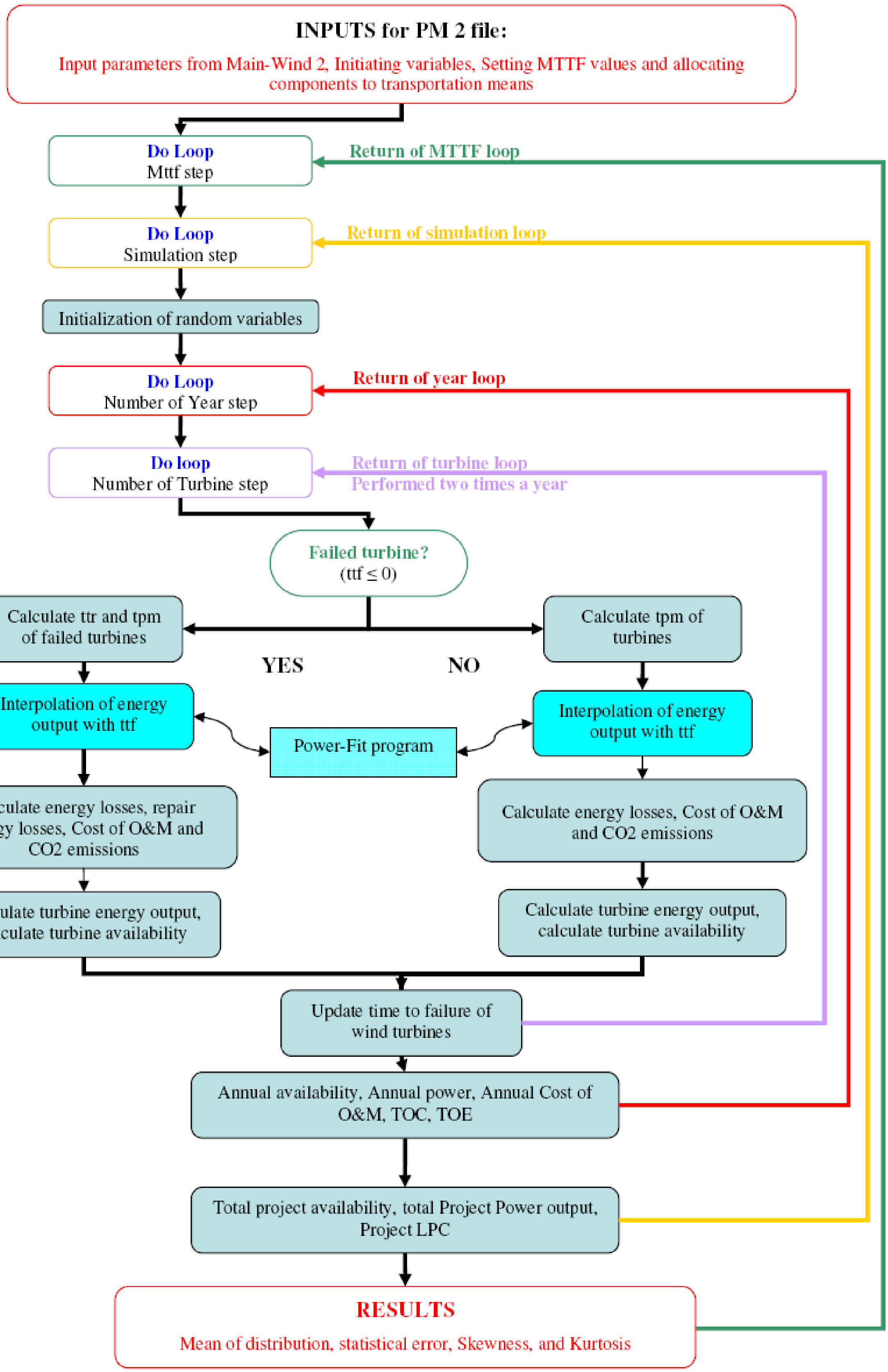


Figure H.2 The structure of Matlab® code for PM 2 program

I.1 Calculation of CO2 emissions for vessels and helicopters

The CO2 emissions for the maintenance of offshore wind turbines are calculated based on the average tonnage of the ships that service the offshore wind farms for large component maintenance, which need large lifting cranes. The equation to calculate the CO2 emissions is shown below:[105,106]

$$RS = WS * MRB * N_j * Distance \tag{I.1}$$

Where:

RS is the total CO2 emissions of an offshore wind turbine maintenance vessel for one wind turbine in a year, measured in grams.

WS is the total weight of the vessel fully loaded including the wind turbine repairable components.

MRB is the mean rate of CO2 emissions from large vessels in grams per kilometre travelled for every tone of the vessel.

N_j is the number of journeys to the wind turbine in a year which directly depends on the failure rate of the wind turbine.

For example, consider a maintenance vessel for offshore wind farms that is used for the repair and exchange of large wind turbine components, e.g. generator and blades, which required the use of large cranes. The reported average weight of this vessel is around 4000 tonnes fully loaded and the average rate of CO2 emission for such a vessel is around 30 grams per kilometre travelled per tonne.[105,106] Considering the above then equation I.1 becomes:

$$RS = WS * MRB * N_j * Distance$$

or

$$RS = 4000 * 30 * N_j * Distance$$

or

$$RS = 120000 * N_j * Distance \text{ (in grams of CO2 for one year)}$$

Similarly the calculations for the helicopters that service the offshore wind farms are based on an Agusta A119 Koala type that is typically used.[160] The helicopters of this type emit 9.6 kilos of CO_2 per gallon consumed for travelling.[160] The fuel tank of the helicopter has 870 litres with an autonomy of 991 km. Using all the above details it is calculated that the helicopters emit 31200 grams of CO_2 per kilometre travelled.

I.2 Average CO2 emissions from bio-diesel fuel

The figures presented in this Appendix give the details for the greenhouse gas emissions when using bio-diesel fuels. These figures are used for the calculation of the CO2 emissions for maintenance expeditions for offshore wind farms in Chapter 6.

AVERAGE BIODIESEL EMISSIONS COMPARED TO CONVENTIONAL DIESEL, ACCORDING TO EPA		
Emission Type	**B100**	**B20**
Regulated		
Total Unburned Hydrocarbons	-67%	-20%
Carbon Monoxide	-48%	-12%
Particulate Matter	-47%	-12%
Nox	+10%	+2% to -2%
Non-Regulated		
Sulfates	-100%	-20%*
PAH (Polycyclic Aromatic Hydrocarbons)**	-80%	-13%
nPAH (nitrated PAH's)**	-90%	-50%***
Ozone potential of speciated HC	-50%	-10%

Figure I.1 Average bio-diesel emissions compared to conventional diesel.[102]

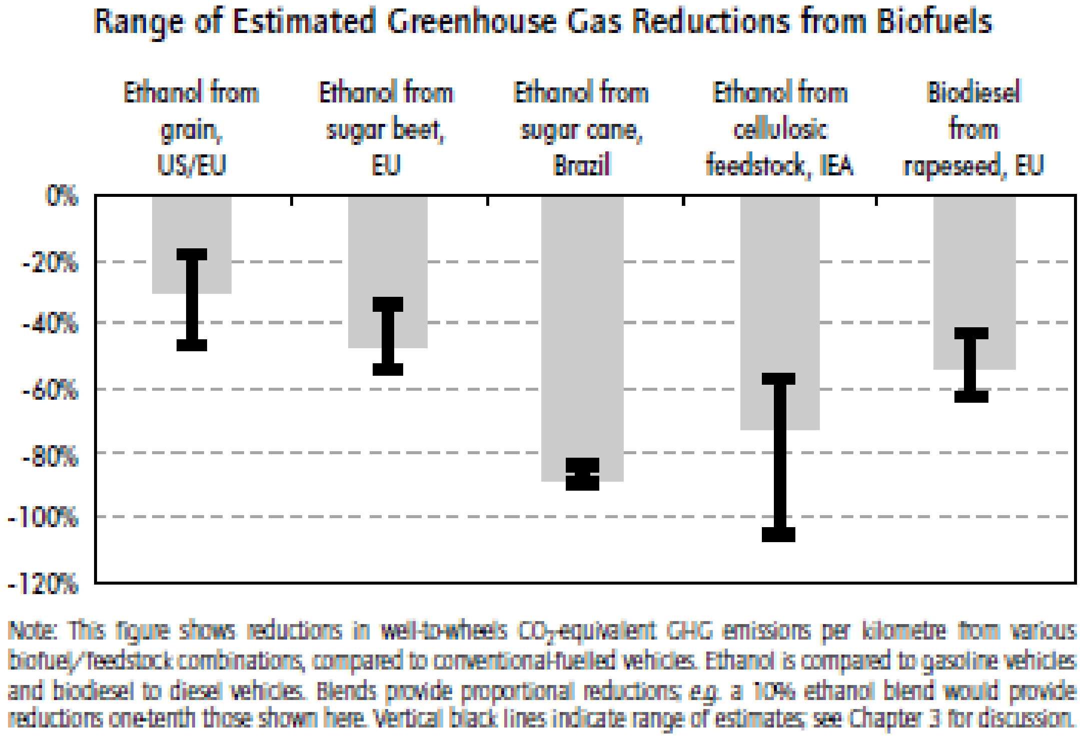


Figure I.2 Range of estimated greenhouse gas reductions achieved by the use of bio-diesel fuel.[102,103,104]

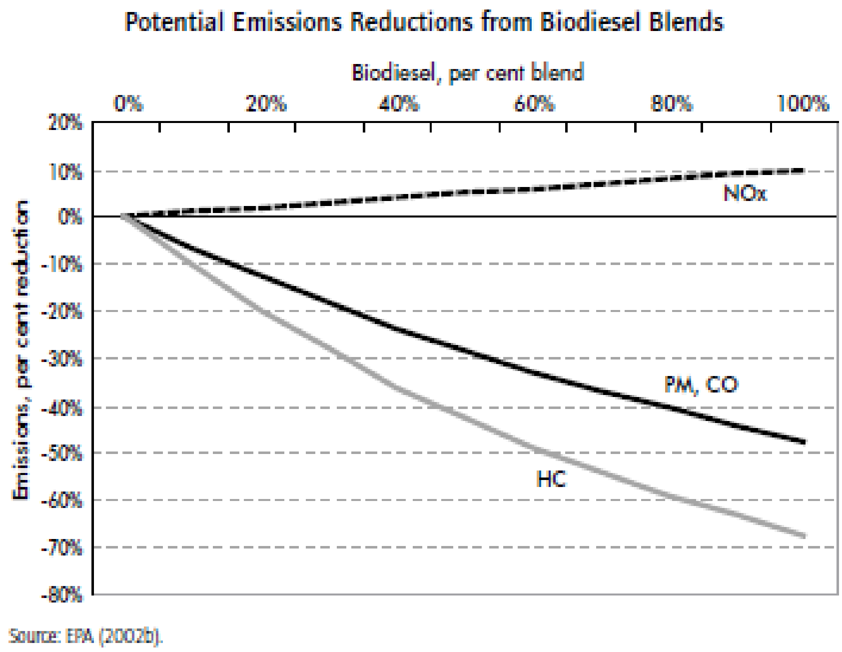


Figure I.3 The potential emissions reductions from bio-diesel blends with conventional fuels.[104]

Estimates of Energy Use and Greenhouse Gas Emissions from Advanced Biofuels from the Novem/ADL Study (1999)

Fuel	Feedstock / location	Process	Well-to-tank: Process energy efficiency (energy in/out)	Well-to-tank: Percent efficiency	Well-to-wheels: CO_2-equivalent GHG emissions g/km	Well-to-wheels: GHG% reduction v. gasoline/diesel
Diesel	petroleum	refining	1.10	91%	198	
Biodiesel	rapeseed (local)	oil to FAME (transesterification)	1.60	62%	123	38%
Biodiesel	soybeans (local)	oil to FAME (transesterification)	1.43	70%	94	53%
Diesel	biomass - eucalyptus (Baltic)	HTU biocrude	1.47	68%	79	60%
Diesel	biomass - eucalyptus (Baltic)	gasification / F-T	2.35	43%	-16	108%
Diesel	biomass - eucalyptus (Baltic)	pyrolysis	3.31	30%	72	64%
DME	biomass - eucalyptus (Baltic)	gasification / DME conversion	1.78	56%	22	89%
Gasoline	petroleum	refining	1.20	83%	231	
Gasoline	biomass - eucalyptus (Baltic)	gasification / F-T	2.71	37%	-10	104%
Ethanol	biomass - poplar (Baltic)	enzymatic hydrolysis (CBP)	1.94	51%	-28	112%
Ethanol	biomass - poplar (Brazil)	enzymatic hydrolysis (CBP)	1.94	51%	-28	112%
Ethanol	biomass - poplar (local with feedstock from Brazil)	enzymatic hydrolysis (CBP)	1.94	51%	-3	101%
Ethanol	corn (local)	fermentation	2.25	45%	65	72%
Hydrogen	biomass - eucalyptus (Baltic)	gasification	2.41	42%	11	95%
CNG	biomass - eucalyptus (local)	gasification	1.69	59%	39	83%

Note: For a discussion of each of the processes listed in this table, see Chapter 2. CBP: combined bioprocessing. F-T: Fischer-Tropsch process.
Source: Novem/ADL (1999).

Figure I.4 Greenhouse gas emissions reductions achieved by the use of bio-fuels.[102,103,104]

Estimates of Production Cost for Advanced Processes

Fuel	Feedstock / location	Process	$/litre gasoline-equivalent
Diesel	petroleum	refining	$0.22
Biodiesel	rapeseed	oil to FAME (transesterification)	$0.80
Diesel	biomass - eucalyptus (Baltic)	HTU	$0.56
Diesel	biomass - eucalyptus (Baltic)	gasification / F-T	$0.68
Diesel	biomass - eucalyptus (Baltic)	pyrolysis	$1.36
DME	biomass - eucalyptus (Baltic)	gasification / DME conversion	$0.47
Gasoline	petroleum	refining	$0.22
Ethanol	biomass - poplar (Baltic)	enzymatic hydrolysis (CBP)	$0.27
Ethanol	biomass - poplar (Brazil)	enzymatic hydrolysis (CBP)	$0.27
Gasoline	biomass - eucalyptus (Baltic)	gasification / F-T	$0.76
Hydrogen	biomass - eucalyptus (Baltic)	gasification	$4.91
CNG	biomass - eucalyptus (Netherlands)	gasification	$0.46

Note: Average gate prices for gasoline and diesel in 1999 in the Netherlands are also shown.
Source: Novem/ADL (1999).

Figure I.5 Estimation of production cost for bio-fuels compared with conventional diesel and gasoline prices.[102,103,104]

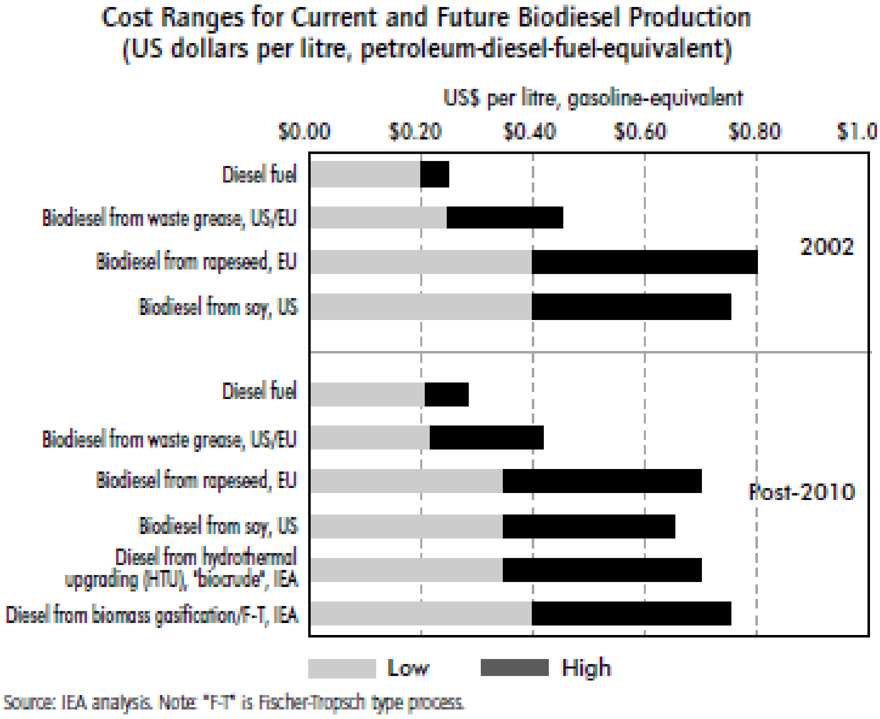


Figure I.6 Cost ranges for current and future bio-diesel production in comparison with conventional diesel fuel.[102,103,104]

J. Failure modes for wind turbine converter systems

It has been concluded in Chapter 4 and Appendix E that the wind turbine components that suffer the highest failure rates is the electrical system. It could be reasonably assumed that the reason for the high failure rates is related to the load condition they are operating within the wind turbines, i.e. full output current at very low output current frequencies.[114] It should be mentioned at this point that that the wind turbine inverter's operation and type depends on the wind turbine system design, e.g. a gearless wind turbine uses a fully rated inverter directly connected to the grid, whilst a doubly fed induction generator wind turbine uses a partially rated inverter connected to the rotor. The reason for high failure rates of the electrical system of a wind turbine has been investigated by a number of studies which all conclude to the fact that the key technical challenge is found on the operating conditions of the inverter system within a wind turbine.[109,110,111,112,113,114]

Considering a wind turbine equipped with a doubly fed induction generator, the main reason for the power semiconductors in the inverter system, i.e. IGBT (insulated gate bipolar transistor), to fail is that most of the time they operate within the maximum thermal stressing zone,[114] which in turn results in thermal fatigue, the reason being for the thermal stresses appearing on the inverter for wind turbines are based on the basic principles of operation of the generator, as compared to other applications of this inverter system. A machine with two pole – pairs has a synchronous speed of 1500 rpm at 50 Hz,[114] i.e. the inverter has to deliver excitation energy within the frequency range of 16,6 Hz (clockwise) to zero Hertz (synchronous generator) to 16,6 Hz (counterclockwise). It has been studied experimentally that in a thermal model of the wind turbine inverter's IGBT that the thermal time constant of the dies is about some milliseconds and that the thermal cycling capability is still limited.[114] This conclusion indicates that the inverter coupled with the rotor of doubly fed induction generator operates most of the time within the maximum thermal stressing zone of a few Hertz, as shown in Figure J.1.[114]

Figure J.1 shows the relationship between the output temperatures of the wind turbine IGBT against its operating frequency, where it can be observed that as the operating frequency decreases the IGBT temperature is increasing significantly.

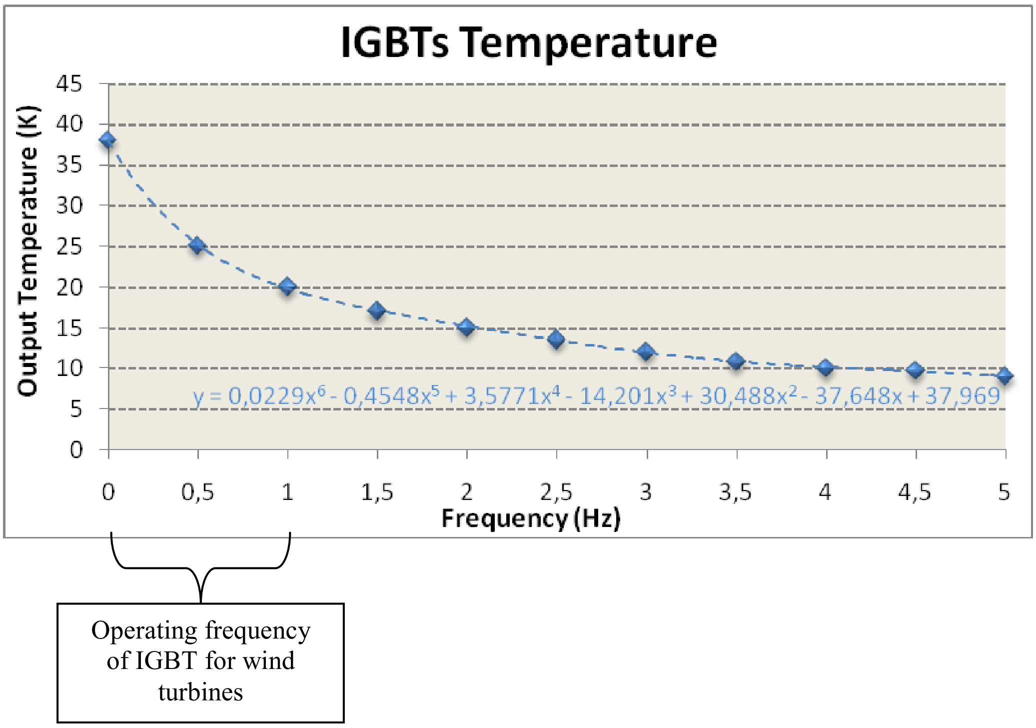


Figure J.1 Output Temperature of the IGBT against its operating frequency. [Graph redrawn from 114]

K. UK's Round 1 and 2 Wind farms

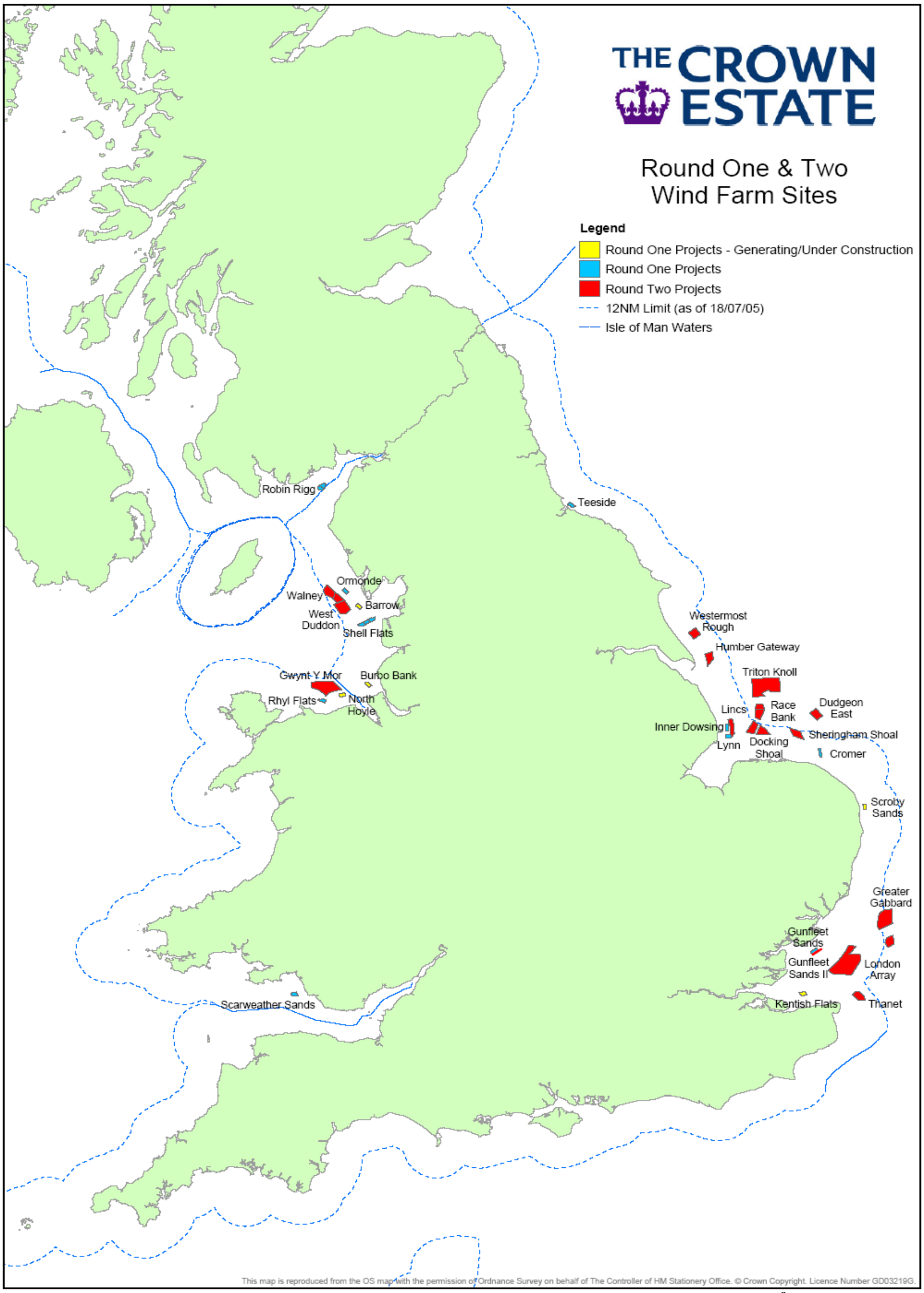


Figure K.1 UK's Round 1 and 2 offshore wind farms[8]

L. The Mathworks Matlab algorithms for the O&M model

L.1.1 Wind Selector Program

```
function varargout = gui_wind_selector4(varargin)
% GUI_WIND_SELECTOR4 M-file for gui_wind_selector4.fig
%      GUI_WIND_SELECTOR4, by itself, creates a new GUI_WIND_SELECTOR4 or raises the↙
existing
%      singleton*.
%
%      H = GUI_WIND_SELECTOR4 returns the handle to a new GUI_WIND_SELECTOR4 or the↙
handle to
%      the existing singleton*.
%
%      GUI_WIND_SELECTOR4('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in GUI_WIND_SELECTOR4.M with the given input arguments.
%
%      GUI_WIND_SELECTOR4('Property','Value',...) creates a new GUI_WIND_SELECTOR4 or↙
raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before gui_wind_selector3_OpeningFunction gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to gui_wind_selector4_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help gui_wind_selector4

% Last Modified by GUIDE v2.5 16-Feb-2010 16:22:38

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @gui_wind_selector4_OpeningFcn, ...
                   'gui_OutputFcn',  @gui_wind_selector4_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before gui_wind_selector4 is made visible.
function gui_wind_selector4_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to gui_wind_selector4 (see VARARGIN)
```

```
% Choose default command line output for gui_wind_selector4
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes gui_wind_selector4 wait for user response (see UIRESUME)
% uiwait(handles.figure1);
initialize_gui(hObject, handles, false);

% --- Outputs from this function are returned to the command line.
function varargout = gui_wind_selector4_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


function initialize_gui(fig_handle, handles, isreset)
% If the metricdata field is present and the reset flag is false, it means
% we are we are just re-initializing a GUI by calling it from the cmd line
% while it is up. So, bail out as we dont want to reset the data.
if isfield(handles, 'gui_inputs') & ~isreset
    return;
end

handles.gui_inputs.save_switch = 0;
handles.gui_inputs.nopm_switch = 0;
handles.gui_inputs.pm1_switch = 0;
handles.gui_inputs.pm2_switch = 0;

handles.gui_inputs.turbines = 0;
handles.gui_inputs.power_rating = 0;
handles.gui_inputs.capacity_factor = 0;
handles.gui_inputs.years = 0;
handles.gui_inputs.discount_rate = 0;
handles.gui_inputs.simulations = 0;
handles.gui_inputs.mttr = 0;
handles.gui_inputs.mtpm_failed = 0;
handles.gui_inputs.mtpm_all = 0;

set(handles.turbines, 'String', handles.gui_inputs.turbines);
set(handles.power_rating,  'String', handles.gui_inputs.power_rating);
set(handles.capacity_factor,  'String', handles.gui_inputs.capacity_factor);
set(handles.years, 'String', handles.gui_inputs.years);
set(handles.discount_rate, 'String', handles.gui_inputs.discount_rate);
set(handles.simulations, 'String', handles.gui_inputs.simulations);
set(handles.mttr, 'String', handles.gui_inputs.mttr);
set(handles.mtpm_failed, 'String', handles.gui_inputs.mtpm_failed);
set(handles.mtpm_all, 'String', handles.gui_inputs.mtpm_all);

% %set(handles.unitgroup, 'SelectedObject', handles.english);
```

```
% set(handles.mynumber3text, 'String', 'Enter a number 3');
% set(handles.text2, 'String', 'Enter a number 2');
% set(handles.mynumber_st, 'String', 'Enter a number');
% set(handles.result_text, 'String', 'Results');


guidata(handles.figure1, handles);




% --- Executes on button press in nopm.
function nopm_Callback(hObject, eventdata, handles)
% hObject    handle to nopm (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of nopm
handles.gui_inputs.pm2_switch = 0;
handles.gui_inputs.nopm_switch = 1;
handles.gui_inputs.pm1_switch = 0;

guidata(handles.figure1, handles);

% --- Executes on button press in pm1.
function pm1_Callback(hObject, eventdata, handles)
% hObject    handle to pm1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of pm1
handles.gui_inputs.pm2_switch = 0;
handles.gui_inputs.nopm_switch = 0;
handles.gui_inputs.pm1_switch = 1;

guidata(handles.figure1, handles);

% --- Executes on button press in pm2.
function pm2_Callback(hObject, eventdata, handles)
% hObject    handle to pm2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of pm2

handles.gui_inputs.pm2_switch = 1;
handles.gui_inputs.nopm_switch = 0;
handles.gui_inputs.pm1_switch = 0;

guidata(handles.figure1, handles);


% --- Executes on selection change in predefined.
function predefined_Callback(hObject, eventdata, handles)
% hObject    handle to predefined (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
```

```
% handles    structure with handles and user data (see GUIDATA)

% Hints: contents = get(hObject,'String') returns predefined contents as cell array
%        contents{get(hObject,'Value')} returns selected item from predefined

handles.gui_inputs.turbines = 100;
handles.gui_inputs.power_rating = 5;
handles.gui_inputs.capacity_factor = 0.35;
handles.gui_inputs.years = 20;
handles.gui_inputs.discount_rate = 0.05;
handles.gui_inputs.simulations = 100;
handles.gui_inputs.mttr = 0.0137;
handles.gui_inputs.mtpm_failed = 0.00275;
handles.gui_inputs.mtpm_all = 0.00275;


set(handles.turbines, 'String', handles.gui_inputs.turbines);
set(handles.power_rating,  'String', handles.gui_inputs.power_rating);
set(handles.capacity_factor,  'String', handles.gui_inputs.capacity_factor);
set(handles.years, 'String', handles.gui_inputs.years);
set(handles.discount_rate, 'String', handles.gui_inputs.discount_rate);
set(handles.simulations, 'String', handles.gui_inputs.simulations);
set(handles.mttr, 'String', handles.gui_inputs.mttr);
set(handles.mtpm_failed, 'String', handles.gui_inputs.mtpm_failed);
set(handles.mtpm_all, 'String', handles.gui_inputs.mtpm_all);

guidata(handles.figure1, handles);

% --- Executes during object creation, after setting all properties.
function predefined_CreateFcn(hObject, eventdata, handles)
% hObject    handle to predefined (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: popupmenu controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function turbines_Callback(hObject, eventdata, handles)
% hObject    handle to turbines (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of turbines as text
%        str2double(get(hObject,'String')) returns contents of turbines as a double

turbines = str2double(get(hObject, 'String'));
if isnan(turbines)
    set(hObject, 'String', 0);
    errordlg('Input must be a number','Error');
end
```

```
% Save the new density value
handles.gui_inputs.turbines = turbines;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function turbines_CreateFcn(hObject, eventdata, handles)
% hObject    handle to turbines (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function power_rating_Callback(hObject, eventdata, handles)
% hObject    handle to power_rating (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of power_rating as text
%        str2double(get(hObject,'String')) returns contents of power_rating as a double


% --- Executes during object creation, after setting all properties.
function power_rating_CreateFcn(hObject, eventdata, handles)
% hObject    handle to power_rating (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function capacity_factor_Callback(hObject, eventdata, handles)
% hObject    handle to capacity_factor (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of capacity_factor as text
%        str2double(get(hObject,'String')) returns contents of capacity_factor as a↙
double


% --- Executes during object creation, after setting all properties.
function capacity_factor_CreateFcn(hObject, eventdata, handles)
% hObject    handle to capacity_factor (see GCBO)
```

```
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function years_Callback(hObject, eventdata, handles)
% hObject    handle to years (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of years as text
%        str2double(get(hObject,'String')) returns contents of years as a double


% --- Executes during object creation, after setting all properties.
function years_CreateFcn(hObject, eventdata, handles)
% hObject    handle to years (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function discount_rate_Callback(hObject, eventdata, handles)
% hObject    handle to discount_rate (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of discount_rate as text
%        str2double(get(hObject,'String')) returns contents of discount_rate as a↙
double


% --- Executes during object creation, after setting all properties.
function discount_rate_CreateFcn(hObject, eventdata, handles)
% hObject    handle to discount_rate (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
end



function simulations_Callback(hObject, eventdata, handles)
% hObject    handle to simulations (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of simulations as text
%        str2double(get(hObject,'String')) returns contents of simulations as a double


% --- Executes during object creation, after setting all properties.
function simulations_CreateFcn(hObject, eventdata, handles)
% hObject    handle to simulations (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function mttr_Callback(hObject, eventdata, handles)
% hObject    handle to mttr (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of mttr as text
%        str2double(get(hObject,'String')) returns contents of mttr as a double


% --- Executes during object creation, after setting all properties.
function mttr_CreateFcn(hObject, eventdata, handles)
% hObject    handle to mttr (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function mtpm_failed_Callback(hObject, eventdata, handles)
% hObject    handle to mtpm_failed (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
```

```
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of mtpm_failed as text
%        str2double(get(hObject,'String')) returns contents of mtpm_failed as a double


% --- Executes during object creation, after setting all properties.
function mtpm_failed_CreateFcn(hObject, eventdata, handles)
% hObject    handle to mtpm_failed (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function mtpm_all_Callback(hObject, eventdata, handles)
% hObject    handle to mtpm_all (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of mtpm_all as text
%        str2double(get(hObject,'String')) returns contents of mtpm_all as a double


% --- Executes during object creation, after setting all properties.
function mtpm_all_CreateFcn(hObject, eventdata, handles)
% hObject    handle to mtpm_all (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in run.
function run_Callback(hObject, eventdata, handles)
% hObject    handle to run (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of run

if handles.gui_inputs.nopm_switch
    disp('not ready')
elseif handles.gui_inputs.pml_switch
    disp('not ready')
```

```
    elseif handles.gui_inputs.pm2_switch
     mainwind_pm2

else disp('no O&M selected')
end

% --- Executes on button press in save_work.
function save_work_Callback(hObject, eventdata, handles)
% hObject    handle to save_work (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of save_work

handles.gui_inputs.save_switch = 1 - handles.gui_inputs.save_switch;
guidata(handles.figure1, handles);




function edit10_Callback(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit10 as text
%        str2double(get(hObject,'String')) returns contents of edit10 as a double


% --- Executes during object creation, after setting all properties.
function edit10_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit11_Callback(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit11 as text
%        str2double(get(hObject,'String')) returns contents of edit11 as a double


% --- Executes during object creation, after setting all properties.
function edit11_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
```

```
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

L.1.2 Main Wind 1 Program

```
% Program: Main Wind 1  version 1.7 (PI)
% Date: 01 Feb 2010 12:30
% Written by: Alexander Karyotakis


clear all
pack


turbines = input ('Enter the number of the wind turbines in the windfarm:  ');
turbine_rating = input ('Enter the turbine power rating (for 5 MW enter 5):    ');
capacity_factor = input ('Enter the expected capacity factor of the wind farm (for 35%
enter 0.35):    ');
years = input ('Enter the project duration (in years): ');
discount = input ('Enter the discount rate (for 5% discount enter 0.05):  ');
simulations = input ('Enter the number of the simulations:  ');
Distance = input ('Enter the distance to shore (in km): ');
Heli_emissions = input ('Enter the Helicopter emissions (in grams/km):  ');
Boat_emissions = input ('Enter the Boat emissions (in grams/km):  ');
mttr = input ('Enter the mean time to repair for the failed turbines (mttr for 3.5 days
enter 0.0096):   ');
mtpm = input ('Enter the mean time for preventive maintenance for the failed turbines
(mtpm for 1 day enter 0.00275):   ');
mtpm_work = input ('Enter the mean time for preventive maintenance for the working
turbines:   ');


avail = zeros(10,1);
power = zeros(10,1);
lpc = zeros(10,1);
TOC1 = zeros(10,1);


%----------------------calculate Powerfit_season1 values------------------%

presic = 7
 x = (0:-10 ^ (-presic):-1);
 powerfit_array = powerfit(x)';
clear x;
%-----------------------------------------------------------------------%

tic
for i=1:10

    mttf(i) = i*0.25;
    [avail(i,:),power(i,:),lpc(i,:),TOC1(i,:),CO2(i,:),k(i,:),k1(i,:)] = pm2(mttf(i),
mttr,mtpm,mtpm_work,turbines,years,discount,capacity_factor,turbine_rating,
powerfit_array,simulations,Distance,Heli_emissions,Vessel_emissions);
    i

end
toc

%------------------------Saving workspace-------------------------------%

clear powerfit_array;
```

```
save d:\temp\mydata; % Always edit 'mydata' with new name

%----------------Always edit 'mydata' with new name-----------------------%


%---------------------Results in graphical form---------------------------%

% figure(1)
%
% plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('mean'),grid
%
% %    Use them when calculating the skewness and accuracy change also
% %    avail = zeros (10,4); above and all the other.
% % subplot(221),plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('mean'),grid
% % subplot(222),plot(mttf,lpc(:,2) ./ lpc(:,1)),xlabel('mttf'),ylabel('Coefficient of↙
Variation'),grid
% % subplot(223),plot(mttf,lpc(:,3)),xlabel('mttf'),ylabel('skewness'),grid
% % subplot(224),plot(mttf,lpc(:,4)),xlabel('mttf'),ylabel('kurtosis'),grid
%
% figure(2)
%
% subplot(211),plot(mttf,avail(:,1)),xlabel('mttf'),ylabel('mean'),title↙
('Availability'),grid
% subplot(212),plot(mttf,power(:,1)),xlabel('mttf'),ylabel('mean'),title('Power'),grid
%
 figure(3)

subplot(221),plot(mttf,avail(:,1)),xlabel('mttf'),ylabel('Availability'),title↙
('Availability'),grid
subplot(222),plot(mttf,power(:,1)),xlabel('mttf'),ylabel('Cumulative Energy Output'),↙
title('Power'),grid
subplot(223),plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('LPC'),title('Levelised↙
Production Cost'),grid
```

L.1.3 PM 1 Program

```
function [avail,power,lpc,TOC1,CO2,k,k1] = pm2(mttf,mttr,mtpm,mtpm_work,turbines,years,↙
discount,capacity_factor,turbine_rating,powerfit_array,simulations,Distance,↙
Heli_emissions,Vessel_emissions)


% Program: PM1 version 1.7 (PI)
% Date: 01 Feb 2010, 12:10
% Written by: Alexander Karyotakis
%
% Comments: Change of CO2 emissions calculations
% Old Comments 2: addaptation of PI with 2PI codes
%
%
%
%-----------------------------outputs explanation------------------------%

% avail - the projects availability
% power - the overall power output
% lpc   - levelized production costs
% CO2   - carbon dioxide emissions

%-------------------------------inputs explanation------------------------%

% mttf            - mean time to failure for each turbine
% mttr            - mean time to repair each failed turbine
% mtpm            - mean time for preventive maintenance of the failed turbines
% mtpm_work       - mean time for preventive maintenance for the working turbines
% turbines        - number of turbines in the wind farm
% years           - project duration
% discount        - interest rate for discount factors
% capacity_factor - The wind farm's capacity factor
% turbine_rating  - The turbine power rating
% simulations     - number of random simulations
% powerfit_array  - pre-calculated powerfit interpolation
% Distance        - distance to shore
% Heli_emissions  - helicopter emissions per kilometer travelled
% Vessel_emissions- vessel emissions per kilometer travelled

%---------------------------parameters explanation------------------------%
%
% ttf                 - time to failure
% ttr                 - time to repair
% tpm                 - time for preventive maintenance
% periods             - 6 months periods between repairs
% turbine_avail       - availability of each wind turbine
% annual_avail        - annual availability of wind farm
% turbine_power       - energy output for each wind turbine
% annual_power        - annual energy output of wind farm
% proj_power          - total energy output of wind farm
% annual_C_om         - annual cost of maintenance
% annual_CO2          - annual CO2 emissions
% proj_CO2            - total CO2 emissions
% I_tot               - CAPEX with decommissioning costs
% C_om                - Cost of maintenance
% TOC                 - Total levelised costs
% repair_power_loss   - The power lost due to repairs
```

```
% power_loss          - The power lost due to preventive maintenance
% presic              - precision of powerfit interpolation

%-------------------------------Variables Initiation----------------------%

ttf = zeros(turbines,1);
ttr = zeros(turbines,1);
tpm = zeros(turbines,1);
power_loss = zeros(turbines,1);
repair_power_loss = zeros(turbines,1);

%--------------------------------Availabilities--------------------------%

turbine_avail = zeros(turbines,1);
annual_avail = zeros(years,1);
proj_avail = zeros(simulations,1);
k2 = zeros(turbines,1);
k1 = zeros(turbines,1);
annual_k = zeros(periods,1);
annual_k1 = zeros(periods,1);
proj_k = zeros(simulations,1);
proj_k1 = zeros(simulations,1);
%-------------------------------------Power--------------------------------%

turbine_power = zeros(turbines,1);
annual_power = zeros(years,1);
proj_power = zeros(simulations,1);

%----------------------------------Cost of O&M---------------------------%

C_om = zeros(turbines,1);
C_om1 = zeros(turbines,1);
C_om2 = zeros(turbines,1);
annual_C_om = zeros(years,1);
TOC = 0;

%----------------------------mttf breakdown-------------------------------%

% Input of Automated component MTTF calculation for the repairs.

MTTF1 = (mttf * 0.03);       % Mean Time To Failure of the Housing
MTTF2 = (mttf * 0.068);      % Mean Time To Failure of the Yaw System
MTTF3 = (mttf * 0.043);      % Mean Time To Failure of the Gearbox
MTTF4 = (mttf * 0.06);       % Mean Time To Failure of Other components
MTTF5 = (mttf * 0.024);      % Mean Time To Failure of the Drive Train
MTTF6 = (mttf * 0.216);      % Mean Time To Failure of the Control System
MTTF7 = (mttf * 0.219);      % Mean Time To Failure of the Electric System
MTTF8 = (mttf * 0.036);      % Mean Time To Failure of the Generator
MTTF9 = (mttf * 0.101);      % Mean Time To Failure of the Blades/Pitch
MTTF10 = (mttf * 0.095);     % Mean Time To Failure of the Hydraulics
MTTF11 = (mttf * 0.05);      % Mean Time To Failure of the Rotor Hub
MTTF12 = (mttf * 0.058);     % Mean Time To Failure of the Mechanical Brakes

MTTF_Heli = (MTTF1 + MTTF2 + MTTF4 + MTTF6 + MTTF7 + MTTF10 + MTTF12)/mttf;
MTTF_Vessel = (MTTF3 + MTTF5 + MTTF8 + MTTF9 + MTTF11)/mttf;
```

```
%--------------------------------CO2 emissions----------------------------%

CO2 = zeros(turbines,1);
annual_CO2 = zeros(periods,1);
proj_CO2 = zeros(simulations,1);

%------------------------------Economic Factors---------------------------%

proj_lpc = zeros(simulations,1);
TOC=zeros(years,1);
proj_TOC = zeros(simulations,1);

% Input the CAPEX of the offshore wind farm on study.
I_tot = 1960000000;

%--------------------------Random number Engine---------------------------%

% Sets the random generation engine to restart for each simulation.
rand('state',0);

%--------------------Cost of Labour and Vessels for OM--------------------%

% Daily rate for hiring helicopters (or small vessel with no crane).
C_PM_Heli = 5000/3;

% Daily rate for hiring vessels (jack-up or crane vessel).
C_CM_Vessel = 25000/3;

% Daily rate for maintenance personnel.
C_crew = 50;

% number of maintenance personnel for preventive maintenance.
N_crew_PM = 2;

% number of maintenance personnel for corrective maintenance.
N_crew_CM = 4;

% Working hours per daily shift.
man_hours = 10;

% cost of labour for preventive maintenance
C_PM_labour = C_crew * N_crew_PM * man_hours;

% cost of labour for corrective maintenance
C_CM_labour = C_crew * N_crew_CM * man_hours;


%--------------------------------multi variables------------------------%

% Month percentage of power output in a year multiplied by the number of
% months.
multi_month_selection = ( 0.058 / 4.33 ) * 52;

multi_var_C_om = turbine_rating * 1000 * 8760;

% Calculation of the presicion of calculations.
```

```
multi_presic = -(length(powerfit_array));

%---------------------Start of Simulations loop--------------------------%

for j = 1:simulations;

    %----------------Generation of random variables-----------------------%

    X = rand(turbines,1);
    ttf = -mttf * (log(X));

    %----One period of maintenance per operational year (Years loop)-----%

    for m = 1:years;

        % ttf reduced by 1 indicating each 12 month period.
        ttf = ttf - 1;

%--------------------------------------ttf > 0 --------------------------%

        ttr(find(ttf>0)) = 0;
        tpm(find(ttf>0)) = mtpm_work * ( log(rand(length(find(ttf>0)),1)) );

        power_loss (find(ttf>0)) = (multi_month_selection) * tpm(find(ttf>0));

        k1=length(tpm(find(ttf>0)));

        CO2(find(ttf>0)) = Heli_emissions * 2 * Distance * k1;

        C_PM_material = unifrnd(5000,10000,1,1);
        C_om(find(ttf>0)) = tpm(find(ttf>0)) * 365 * (C_PM_labour + C_PM_Heli) -↙
C_PM_material;

        turbine_avail(find(ttf>0)) = 1 + tpm(find(ttf>0));
        turbine_power(find(ttf>0)) = 1 + power_loss(find(ttf>0));

        random_x = unifrnd(0,0.1,1,1);
        ttf(find(ttf>0)) = (1 + random_x) .* ttf(find(ttf>0));
        clear random_x;

%--------------------------------------ttf =< 0 -------------------------%

        ttr(find(ttf<=0)) = mttr * log(rand(length(find(ttf<=0)),1));
        tpm(find(ttf<=0)) = mtpm * log(rand(length(find(ttf<=0)),1));

        k2 = length(ttr(find(ttf<=0)));


        CO2_Heli1(find(ttf<=0)) = Heli_emissions * MTTF_Heli * 2 * Distance * k2;
        CO2_Vessel1(find(ttf<=0)) = Vessel_emissions * MTTF_Vessel * 2 * Distance * k2;

        CO2(find(ttf<=0)) = CO2_Vessel1(find(ttf<=0)) + CO2_Heli1(find(ttf<=0));

        power_loss(find(ttf<=0)) = (multi_month_selection) * tpm(find(ttf<=0));
        repair_power_loss(find(ttf<=0)) = (multi_month_selection) * ttr(find(ttf<=0));
```

```
        C_PM_material = unifrnd(5000,10000,1,1);
        C_CM_material = unifrnd(5000,15000,1,1);
        C_om1(find(ttf<=0)) = MTTF_Heli * (( ttr(find(ttf<=0)) * 365 * (C_PM_labour +↙
C_PM_Heli) ) + ( tpm(find(ttf<=0)) * 365 * (C_PM_labour + C_PM_Heli) ) -↙
C_PM_material);
        C_om2(find(ttf<=0)) = MTTF_Vessel * (( ttr(find(ttf<=0)) * 365 * (C_CM_labour +↙
C_CM_Vessel) ) + ( tpm(find(ttf<=0)) * 365 * (C_PM_labour + C_PM_Heli) ) -↙
C_CM_material);
        C_om(find(ttf<=0)) = C_om1(find(ttf<=0)) + C_om2(find(ttf<=0));

        power_out = powerfit_array(floor((multi_presic) * ttf(find(ttf<=0))) + 1);

        turbine_avail(find(ttf<=0)) = ( 1 + ttf(find(ttf<=0)) ) .* ( 1 + ttr(find↙
(ttf<=0)) + tpm(find(ttf<=0)) );

        turbine_power(find(ttf<=0)) = ( (power_out / 100) + power_loss(find(ttf<=0)) +↙
repair_power_loss(find(ttf<=0)) );

        ttf_before_tpm = ttf;

        ttf(find(ttf<=0)) = - mttf * log(rand(length(find(ttf<=0)),1));

        random_y = unifrnd(0,0.1,1,1);

        ttf(find(ttf_before_tpm<=0)) = (1 + random_y) .* ttf(find(ttf_before_tpm<=0));
        clear random_y; clear ttf_before_tpm;



        annual_avail(m) = mean(turbine_avail);
        annual_power(m) = sum(turbine_power);
        annual_C_om(m) = sum(C_om);
        annual_CO2(m) = sum(CO2);
        annual_k(m) = sum(k2);
        annual_k1(m) = sum(k1);
        TOC(m) = (1 / ((1 + discount) ^ (-m))) .* annual_C_om(m);

    end


    %------------------Calculation of project variables-------------------%

    proj_TOC(j) = sum(TOC);

    proj_power(j) = sum(annual_power) * capacity_factor * multi_var_C_om;

    proj_lpc(j) = ( I_tot - proj_TOC(j) ) / proj_power(j);

    proj_avail(j) = mean(annual_avail);

    proj_k(j) = sum(annual_k);

    proj_k1(j) = sum(annual_k1);

    proj_CO2(j) = mean(annual_CO2);
```

```
    %-----------------Generate histograms from variables-------------------%

    % Uncomment this paragraph to run the histograms for accuracy of
    % results. Also uncomment the accuracy of results sections below.

    % figure(1)
    % [nf,xout] = hist(proj_avail,50), h1 = bar(xout,nf,'hist');
    % histfit(proj_avail,50);
    % h = findobj(gca,'Type','patch');
    % set(h,'FaceColor','b','EdgeColor','w');
    % xlabel('Availability','FontSize',14);
    % ylabel('Frequency','FontSize',14);
    % end
    % skew = skewness(proj_avail)
    % kurt = kurtosis(proj_avail)
    % deviate = std(proj_avail)
    % y_y = num2str(deviate);
    % gtext(['standard deviation = ' y_y])
    % l = num2str(kurt);
    % gtext(['kurtosis = ' l])
    % l2 = num2str(skew);
    % gtext(['skewness = ' l2])

end


%--------------------Calculation of simulations' variables----------------%

avail = mean(proj_avail);
power = mean(proj_power);
lpc   = mean(proj_lpc);
TOC1  = mean(proj_TOC);
k = mean(proj_k);
k1 = mean(proj_k1);
CO2 = mean(proj_CO2);



%-------------------Accuracy of results calculation----------------------%

% Uncomment to calculate for accuracy of results with the histograms

% avail = [ mean(proj_avail), std(proj_avail), skewness(proj_avail), kurtosis↙
(proj_avail) ];
% power = [ mean(proj_power), std(proj_power), skewness(proj_power), kurtosis↙
(proj_power) ];
% lpc   = [ mean(proj_lpc), std(proj_lpc), skewness(proj_lpc), kurtosis(proj_lpc) ];
```

L.1.4 PowerFit Program for PM 1 Program

```
function power_out = powerfit(ttf)

% Syntax: function power_out = powerfit_season(ttf)
% Version 1.7
% Date: 10 Feb 2010
% Written by:  Alexander Karyotakis
%
% Powerfit program interpolates the energy output from the wind farm with the ttf
values.
%
% Output:
%       power_out - power output in percentage of total.
% Input:
%       ttf - time to failure of the turbine.
%
% Values in table k: first column - ttf value, second column - power_out:
k=[
    0    100
-0.0833  94.4
-0.1666  87.3
-0.2499  79.2
-0.3332  69.1
-0.4165  58.6
-0.4998  47.6
-0.5831  37.2
-0.6664  27.5
-0.7497  18.7
-0.833   11.5
-0.9163  5.8
-1       0];

% interpolation algorithm.
power_out = interp1(k(:,1),k(:,2),ttf,'cubic');
```

L.1.5 Main Wind 2 Program

```
% Program: Main Wind 2  version 1.7 (2PI)
% Date: 01 Feb 2010 12:35
% Written by: Alexander Karyotakis


% Comments: Changed boat to vessel and figures
% old Changed the mttf for 0 to 2.5 according to new pm2 file


clear all
pack


turbines = input ('Enter the number of the wind turbines in the windfarm:  ');
turbine_rating = input ('Enter the turbine power rating (for 5 MW enter 5):    ');
capacity_factor = input ('Enter the expected capacity factor of the wind farm (for 35%↙
enter 0.35):    ');
years = input ('Enter the project duration (in years): ');
discount = input ('Enter the discount rate (for 5% discount enter 0.05):  ');
simulations = input ('Enter the number of the simulations:  ');
Distance = input ('Enter the distance to shore (in km): ');
Heli_emissions = input ('Enter the Helicopter emissions (in grams/km):  ');
Vessel_emissions = input ('Enter the vessel emissions (in grams/km):  ');
mttr = input ('Enter the mean time to repair for the failed turbines (mttr for 3.5 days↙
enter 0.0095):   ');
mtpm = input ('Enter the mean time for preventive maintenance for the failed turbines↙
(mtpm for 1 day enter 0.00275):   ');
mtpm_work = input ('Enter the mean time for preventive maintenance for the working↙
turbines:    ');


avail = zeros(10,1);
power = zeros(10,1);
lpc = zeros(10,1);
TOC1 = zeros(10,1);

%----------------------calculate Powerfit_season1 values------------------%

presic1 = 7
 x = (0:-10 ^ (-presic1):-1);
 powerfit_season1_array = powerfit_season1(x)';
clear x;
%-----------------------------------------------------------------------%


%----------------------calculate Powerfit_season2 values------------------%

presic2 = 7
 x = (0:-10 ^ (-presic2):-1);
 powerfit_season2_array = powerfit_season2(x)';
clear x;
%-----------------------------------------------------------------------%

tic
for i=1:10
```

```
    mttf(i) = i*0.25;
    [avail(i,:),power(i,:),lpc(i,:),TOC1(i,:),CO2(i,:),k(i,:),k1(i,:)] = pm2(mttf(i),↙
mttr,mtpm,mtpm_work,turbines,years,discount,capacity_factor,turbine_rating,↙
powerfit_season1_array,powerfit_season2_array,simulations,Distance,Heli_emissions,↙
Vessel_emissions);
    i

end
toc

%-------------------------Saving workspace--------------------------------%

clear powerfit_season1_array;
clear powerfit_season2_array;

%save d:\temp\mydata; % Always edit 'mydata' with new name

%----------------Always edit 'mydata' with new name-----------------------%

% figure(1)
%
% plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('mean'),grid
%
% %    Use them when calculating the skewness and accuracy change also
% %    avail = zeros (10,4); above and all the other.
% % subplot(221),plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('mean'),grid
% % subplot(222),plot(mttf,lpc(:,2) ./ lpc(:,1)),xlabel('mttf'),ylabel('Coefficient of↙
Variation'),grid
% % subplot(223),plot(mttf,lpc(:,3)),xlabel('mttf'),ylabel('skewness'),grid
% % subplot(224),plot(mttf,lpc(:,4)),xlabel('mttf'),ylabel('kurtosis'),grid
%
% figure(2)
%
% subplot(211),plot(mttf,avail(:,1)),xlabel('mttf'),ylabel('mean'),title↙
('Availability'),grid
% subplot(212),plot(mttf,power(:,1)),xlabel('mttf'),ylabel('mean'),title('Power'),grid
%
 figure(3)

subplot(221),plot(mttf,avail(:,1)),xlabel('mttf'),ylabel('Availability'),title↙
('Availability'),grid
subplot(222),plot(mttf,power(:,1)),xlabel('mttf'),ylabel('Cumulative Energy Output'),↙
title('Power'),grid
subplot(223),plot(mttf,lpc(:,1)),xlabel('mttf'),ylabel('LPC'),title('Levelised↙
Production Cost'),grid
```

L.1.6 PM 2 Program

```
function [avail,power,lpc,TOC1,CO2,k,k1] = pm2(mttf,mttr,mtpm,mtpm_work,turbines,years,↙
discount,capacity_factor,turbine_rating,powerfit_season1_array,powerfit_season2_array,↙
simulations,Distance,Heli_emissions,Vessel_emissions)


% Program: PM2 version 1.7 (2 PI)
% Date: 01 Feb 2010, 12:11
% Written by: Alexander Karyotakis

% Comments: Change of C_CM_vessel and including unifrnd() for repair costs
% Old comments: Changed the CO2 emissions calculations
% Old Comments1: Changed the discount equation to (-m)
% Old Comments2: Changed the powerfit file to adjust the power output to correct
% interpolation. Energy output now starts from 0%
% +++ Comments: Changed the MTTF_Heli and MTTF_Vessel
% +++ Comments: Changed Itot using 0.75 instead of 1.5
% +++ Comments: Changed the cost of heli and vessels to devide by 3 for 3
% visits per expedition
% Old Comments: Integration of the number of failures of wind turbines (k)

%------------------------------outputs explanation------------------------%

% avail - the projects availability
% power - the overall power output
% lpc   - levelized production costs
% CO2   - carbon dioxide emissions

%-------------------------------inputs explanation------------------------%

% mttf            - mean time to failure for each turbine
% mttr            - mean time to repair each failed turbine
% mtpm            - mean time for preventive maintenance of the failed turbines
% mtpm_work       - mean time for preventive maintenance for the working turbines
% turbines        - number of turbines in the wind farm
% years           - project duration
% discount        - interest rate for discount factors
% capacity_factor - The wind farm's capacity factor
% turbine_rating  - The turbine power rating
% simulations     - number of random simulations
% powerfit_array  - pre-calculated powerfit interpolation
% Distance        - distance to shore
% Heli_emissions  - helicopter emissions per kilometer travelled
% Vessel_emissions- vessel emissions per kilometer travelled

%---------------------------parameters explanation------------------------%

% ttf                 - time to failure
% ttr                 - time to repair
% tpm                 - time for preventive maintenance
% periods             - 6 months periods between repairs
% turbine_avail       - availability of each wind turbine
% annual_avail        - annual availability of wind farm
% turbine_power       - energy output for each wind turbine
% annual_power        - annual energy output of wind farm
% proj_power          - total energy output of wind farm
% annual_C_om         - annual cost of maintenance
```

```
% annual_CO2           - annual CO2 emissions
% proj_CO2             - total CO2 emissions
% I_tot                - CAPEX with decommissioning costs
% C_om                 - Cost of maintenance
% TOC                  - Total levelised costs
% repair_power_loss    - The power lost due to repairs
% power_loss           - The power lost due to preventive maintenance
% presic               - precision of powerfit interpolation

%------------------------------Variables Initiation----------------------%

periods = years * 2;
ttf = zeros(turbines,1);
ttr = zeros(turbines,1);
tpm = zeros(turbines,1);
power_loss = zeros(turbines,1);
repair_power_loss = zeros(turbines,1);

%--------------------------------Availabilities---------------------------%

turbine_avail = zeros(turbines,1);
annual_avail = zeros(periods,1);
proj_avail = zeros(simulations,1);
k2 = zeros(turbines,1);
k1 = zeros(turbines,1);
annual_k = zeros(periods,1);
annual_k1 = zeros(periods,1);
proj_k = zeros(simulations,1);
proj_k1 = zeros(simulations,1);

%-------------------------------------Power-------------------------------%

turbine_power = zeros(turbines,1);
annual_power = zeros(periods,1);
proj_power = zeros(simulations,1);

%-----------------------------------Cost of O&M---------------------------%

C_om = zeros(turbines,1);
C_om1 = zeros(turbines,1);
C_om2 = zeros(turbines,1);
annual_C_om = zeros(periods,1);
TOC = 0;

%---------------------------mttf breakdown------------------------------%

% Input of Automated component MTTF calculation for the repairs.

MTTF1 = (mttf * 0.03);       % Mean Time To Failure of the Housing
MTTF2 = (mttf * 0.068);      % Mean Time To Failure of the Yaw System
MTTF3 = (mttf * 0.043);      % Mean Time To Failure of the Gearbox
MTTF4 = (mttf * 0.06);       % Mean Time To Failure of Other components
MTTF5 = (mttf * 0.024);      % Mean Time To Failure of the Drive Train
MTTF6 = (mttf * 0.216);      % Mean Time To Failure of the Control System
MTTF7 = (mttf * 0.219);      % Mean Time To Failure of the Electric System
MTTF8 = (mttf * 0.036);      % Mean Time To Failure of the Generator
```

```
MTTF9 = (mttf * 0.101);      % Mean Time To Failure of the Blades/Pitch
MTTF10 = (mttf * 0.095);     % Mean Time To Failure of the Hydraulics
MTTF11 = (mttf * 0.05);      % Mean Time To Failure of the Rotor Hub
MTTF12 = (mttf * 0.058);     % Mean Time To Failure of the Mechanical Brakes

MTTF_Heli = (MTTF1 + MTTF2 + MTTF4 + MTTF6 + MTTF7 + MTTF10 + MTTF12)/mttf;
MTTF_Vessel = (MTTF3 + MTTF5 + MTTF8 + MTTF9 + MTTF11)/mttf;

%--------------------------------CO2 emissions----------------------------%

CO2 = zeros(turbines,1);
annual_CO2 = zeros(periods,1);
proj_CO2 = zeros(simulations,1);

%------------------------------Economic Factors---------------------------%

proj_lpc = zeros(simulations,1);
TOC=zeros(periods,1);
proj_TOC = zeros(simulations,1);

% Input the CAPEX of the offshore wind farm on study.
I_tot = 1960000000;

%--------------------------Random number Engine---------------------------%

% Sets the random generation engine to restart for each simulation.
rand('state',0);

%--------------------Cost of Labour and Vessels for OM--------------------%

% Daily rate for hiring helicopters (or small vessel with no crane).
C_PM_Heli = 5000/3;

% Daily rate for hiring vessels (jack-up or crane vessel).
C_CM_Vessel = 25000/3;

% Daily rate for maintenance personnel.
C_crew = 50;

% number of maintenance personnel for preventive maintenance.
N_crew_PM = 2;

% number of maintenance personnel for corrective maintenance.
N_crew_CM = 4;

% Working hours per daily shift.
man_hours = 10;

% cost of labour for preventive maintenance
C_PM_labour = C_crew * N_crew_PM * man_hours;

% cost of labour for corrective maintenance
C_CM_labour = C_crew * N_crew_CM * man_hours;


%---------------------------------multi variables-------------------------%
```

```
% Month percentage of power output in a year multiplied by the number of
% months.
multi_month_selection_Oct = ( 0.088 / 4.33) * 52;
multi_month_selection_May = ( 0.071 / 4.33) * 52;

multi_var_C_om = turbine_rating * 1000 * 8760;

% Calculation of the presicion of calculations.
multi_presic1 = -(length(powerfit_season1_array));
multi_presic2 = -(length(powerfit_season2_array));


%----------------------Start of Simulations loop-------------------------%

for j = 1:simulations;

    %----------------Generation of random variables----------------------%

    X = rand(turbines,1);
    ttf = -mttf * (log(X));

    %----Two periods of maintenance per operational year (Years loop)-----%
    for m = 1:periods;

        % ttf reduced by 0.5 indicating each 6 month period.
        ttf = ttf - 0.5;

        % Checks if m is odd or even number and assigns a period. rem
        % command treats period 2 as 1st.
        if rem(m,2)==0;

            %------------------------ttf > 0 ---------------------------%
            ttf = ttf - 0.5;

            ttr(find(ttf>0)) = 0;
            tpm(find(ttf>0)) = mtpm_work * ( log(rand(length(find(ttf>0)),1)) );

            k1 = length(tpm(find(ttf>0)));

            CO2(find(ttf>0)) = Heli_emissions * 2 * Distance * k1;

            power_loss(find(ttf>0)) = (multi_month_selection_May) * tpm(find(ttf>0));

            C_PM_material = unifrnd(5000,10000,1,1);
            C_om(find(ttf>0)) = tpm(find(ttf>0)) * 365 * (C_PM_labour + C_PM_Heli) -↙
C_PM_material;

            turbine_avail(find(ttf>0)) = 1 + tpm(find(ttf>0));
            turbine_power(find(ttf>0)) = 1 + power_loss(find(ttf>0));

            random_x = unifrnd(0,0.1,1,1);
            ttf(find(ttf>0)) = (1 + random_x) .* ttf(find(ttf>0));
            clear random_x;

            %-------------------------ttf =< 0 -------------------------%
```

```
                ttr(find(ttf<=0)) = mttr * log(rand(length(find(ttf<=0)),1));
                tpm(find(ttf<=0)) = mtpm * log(rand(length(find(ttf<=0)),1));

                k2 = length(ttr(find(ttf<=0)));

                CO2_Heli1(find(ttf<=0)) = Heli_emissions * MTTF_Heli * 2 * Distance * k2;
                CO2_Vessel1(find(ttf<=0)) = Vessel_emissions * MTTF_Vessel * 2 * Distance *↙
k2;

                CO2(find(ttf<=0)) = CO2_Vessel1(find(ttf<=0)) + CO2_Heli1(find(ttf<=0));

                power_loss(find(ttf<=0)) = (multi_month_selection_May) * tpm(find(ttf<=0));
                repair_power_loss(find(ttf<=0)) = (multi_month_selection_May) * ttr(find↙
(ttf<=0));

                C_PM_material = unifrnd(5000,10000,1,1);
                C_CM_material = unifrnd(5000,15000,1,1);
                C_om1(find(ttf<=0)) = MTTF_Heli * (( ttr(find(ttf<=0)) * 365 * (C_PM_labour↙
+ C_PM_Heli) ) + ( tpm(find(ttf<=0)) * 365 * (C_PM_labour + C_PM_Heli) ) -↙
C_PM_material);
                C_om2(find(ttf<=0)) = MTTF_Vessel * (( ttr(find(ttf<=0)) * 365 *↙
(C_CM_labour + C_CM_Vessel) ) + ( tpm(find(ttf<=0)) * 365 * (C_PM_labour + C_PM_Heli) )↙
- C_CM_material);
                C_om(find(ttf<=0)) = C_om1(find(ttf<=0)) + C_om2(find(ttf<=0));

                power_out2 = powerfit_season2_array(floor((multi_presic2) * ttf(find↙
(ttf<=0))) + 1);

                turbine_avail(find(ttf<=0)) = ( 1 + ttf(find(ttf<=0)) ) .* ( 1 + ttr(find↙
(ttf<=0)) + tpm(find(ttf<=0)) );

                turbine_power(find(ttf<=0)) = ( (power_out2 / 100) + power_loss(find↙
(ttf<=0)) + repair_power_loss(find(ttf<=0)) );


                ttf_before_tpm = ttf;

                ttf(find(ttf<=0)) = - mttf * log(rand(length(find(ttf<=0)),1));

                random_y = unifrnd(0,0.1,1,1);

                ttf(find(ttf_before_tpm<=0)) = (1 + random_y) .* ttf(find↙
(ttf_before_tpm<=0));
                clear random_y; clear ttf_before_tpm;

            else

                %-------------------------ttf > 0 ---------------------------%

                ttr(find(ttf>0)) = 0;
                tpm(find(ttf>0)) = mtpm_work * ( log(rand(length(find(ttf>0)),1)) );

                k1 = length(tpm(find(ttf>0)));

                CO2(find(ttf>0)) = Heli_emissions * 2 * Distance * k1;
```

```
            power_loss(find(ttf>0)) = (multi_month_selection_Oct) * tpm(find(ttf>0));

            C_PM_material = unifrnd(5000,10000,1,1);
            C_om(find(ttf>0)) = tpm(find(ttf>0)) * 365 * (C_PM_labour + C_PM_Heli) -↙
C_PM_material;

            turbine_avail(find(ttf>0)) = 1 + tpm(find(ttf>0));
            turbine_power(find(ttf>0)) = 1 + power_loss(find(ttf>0));

            random_x = unifrnd(0,0.1,1,1);
            ttf(find(ttf>0)) = (1 + random_x) .* ttf(find(ttf>0));
            clear random_x;

            %---------------------------------------ttf =< 0 --------------------------%

            ttr(find(ttf<=0)) = mttr * log(rand(length(find(ttf<=0)),1));
            tpm(find(ttf<=0)) = mtpm * log(rand(length(find(ttf<=0)),1));

            k2 = length(ttr(find(ttf<=0)));

            CO2_Heli2(find(ttf<=0)) = Heli_emissions * MTTF_Heli * 2 * Distance * k2;
            CO2_Vessel2(find(ttf<=0)) = Vessel_emissions * MTTF_Vessel * 2 * Distance *↙
k2;

            CO2(find(ttf<=0)) = CO2_Vessel2(find(ttf<=0)) + CO2_Heli2(find(ttf<=0));

            power_loss(find(ttf<=0)) = (multi_month_selection_Oct) * tpm(find(ttf<=0));
            repair_power_loss(find(ttf<=0)) = (multi_month_selection_Oct) * ttr(find↙
(ttf<=0));

            C_PM_material = unifrnd(5000,10000,1,1);
            C_CM_material = unifrnd(5000,15000,1,1);
            C_om1(find(ttf<=0)) = MTTF_Heli * (( ttr(find(ttf<=0)) * 365 * (C_PM_labour↙
+ C_PM_Heli) ) + ( tpm(find(ttf<=0)) * 365 * (C_PM_labour + C_PM_Heli) ) -↙
C_PM_material);
            C_om2(find(ttf<=0)) = MTTF_Vessel * (( ttr(find(ttf<=0)) * 365 *↙
(C_CM_labour + C_CM_Vessel) ) + ( tpm(find(ttf<=0)) * 365 * (C_PM_labour + C_PM_Heli) )↙
- C_CM_material);
            C_om(find(ttf<=0)) = C_om1(find(ttf<=0)) + C_om2(find(ttf<=0));

            power_out1 = powerfit_season1_array(floor((multi_presic1) * ttf(find↙
(ttf<=0))) + 1);

            turbine_avail(find(ttf<=0)) = ( 1 + ttf(find(ttf<=0)) ) .* ( 1 + ttr(find↙
(ttf<=0)) + tpm(find(ttf<=0)) );

            turbine_power(find(ttf<=0)) = ( (power_out1 / 100) + power_loss(find↙
(ttf<=0)) + repair_power_loss(find(ttf<=0)) );

            ttf_before_tpm = ttf;

            ttf(find(ttf<=0)) = - mttf * log(rand(length(find(ttf<=0)),1));

            random_y = unifrnd(0,0.1,1,1);
```

```
            ttf(find(ttf_before_tpm<=0)) = (1 + random_y) .* ttf(find↙
(ttf_before_tpm<=0));
            clear random_y; clear ttf_before_tpm;

        end

        annual_k(m) = sum(k2);
        annual_k1(m) = sum(k1);

        annual_avail(m) = mean(turbine_avail);
        annual_power(m) = sum(turbine_power);
        annual_C_om(m) = sum(C_om);
        annual_CO2(m) = sum(CO2);
        TOC(m) = (1 / ((1 + discount/2) ^ (-m))) .* annual_C_om(m);

    end


    %------------------Calculation of project variables-------------------%

    proj_k(j) = sum(annual_k);

    proj_k1(j) = sum(annual_k1);

    proj_TOC(j) = sum(TOC);

    proj_power(j) = sum(annual_power) * capacity_factor * multi_var_C_om;

    proj_lpc(j) = ( I_tot - proj_TOC(j) ) / proj_power(j);

    proj_avail(j) = mean(annual_avail);

    proj_CO2(j) = mean(annual_CO2);


    %-----------------Generate histograms from variables-------------------%

    % Uncomment this paragraph to run the histograms for accuracy of
    % results. Also uncomment the accuracy of results sections below.

    % figure(1)
    % [nf,xout] = hist(proj_avail,50), h1 = bar(xout,nf,'hist');
    % histfit(proj_avail,50);
    % h = findobj(gca,'Type','patch');
    % set(h,'FaceColor','b','EdgeColor','w');
    % xlabel('Availability','FontSize',14);
    % ylabel('Frequency','FontSize',14);
    % end
    % skew = skewness(proj_avail)
    % kurt = kurtosis(proj_avail)
    % deviate = std(proj_avail)
    % y_y = num2str(deviate);
    % gtext(['standard deviation = ' y_y])
    % l = num2str(kurt);
    % gtext(['kurtosis = ' l])
    % l2 = num2str(skew);
```

```
    % gtext(['skewness = ' 12])

end

%--------------------Calculation of simulations' variables----------------%

k = mean(proj_k);
k1 = mean(proj_k1);
avail = mean(proj_avail);
power = mean(proj_power);
lpc   = mean(proj_lpc);
TOC1  = mean(proj_TOC);
CO2 = mean(proj_CO2);


%-------------------Accuracy of results calculation-----------------------%

% Uncomment to calculate for accuracy of results with the histograms

% avail = [ mean(proj_avail), std(proj_avail), skewness(proj_avail), kurtosis↙
(proj_avail) ];
% power = [ mean(proj_power), std(proj_power), skewness(proj_power), kurtosis↙
(proj_power) ];
% lpc   = [ mean(proj_lpc), std(proj_lpc), skewness(proj_lpc), kurtosis(proj_lpc) ];
```

L.1.7 PowerFit season 1 Program

```
function power_out1 = powerfit_season1(ttf)

% Syntax: function power_out1 = powerfit_season1(ttf)
% Version 1.7
% Date: 01 Feb 2010
% Written by:  Alexander Karyotakis


% Powerfit program interpolates the energy output from the wind farm with the ttf
values.
% For Season 1 between October and May.
% The planned intervention takes place in October
%
% Output:
%       power_out - power output in percentage of total.
% Input:
%       ttf - time to failure of the turbine.
%
% Values in table k: first column - ttf value, second column - power_out:

k=[
    0   68.6
-0.071  60.5
-0.142  50.4
-0.213  39.9
-0.284  28.9
-0.355  18.5
-0.426  8.8
-0.5    0];

% interpolation algorithm.
power_out1 = interp1(k(:,1),k(:,2),ttf,'cubic');
```

L.1.8 PowerFit season 2 Program

```
function power_out2 = powerfit_season2(ttf)

% Syntax: function power_out2 = powerfit_season2(ttf)
% Version 1.7
% Date: 01 Feb 2010
% Written by:  Alexander Karyotakis


% Powerfit interpolates the energy output from the wind farm with the ttf values.
% For Season 2 between May and October.
% The planned intervention takes place in May.
%
% Output:
%       power_out - power output in percentage of total.
% Input:
%       ttf - time to failure of the turbine.
%
% Values in table k: first column - ttf value, second column - power_out:

k=[
  0   31.4
-0.1  24.2
-0.2  18.5
-0.3  12.7
-0.4  7.1
-0.5  0];

% interpolation algorithm.
power_out2 = interp1(k(:,1),k(:,2),ttf,'cubic');
```

L.1.9 Results multi-plot Program

```
function createfigure(converters1, newlpc1, S1, C1, X1, Y1, newlpc2, Y2, newlpc3, Y3,↙
newlpc4, Y4)
%CREATEFIGURE(CONVERTERS1,NEWLPC1,S1,C1,X1,Y1,NEWLPC2,Y2,NEWLPC3,Y3,NEWLPC4,Y4)
%  CONVERTERS1:  scatter x
%  NEWLPC1:  scatter y
%  S1:  scatter s
%  C1:  scatter c
%  X1:  vector of x data
%  Y1:  vector of y data
%  NEWLPC2:  scatter y
%  Y2:  vector of y data
%  NEWLPC3:  scatter y
%  Y3:  vector of y data
%  NEWLPC4:  scatter y
%  Y4:  vector of y data

%  Auto-generated by MATLAB on 16-Feb-2010 16:59:33

% Create figure
figure1 = figure('PaperType','a4letter','PaperSize',[29.68 20.98],...
    'PaperOrientation','landscape');

% Create axes
axes1 = axes('Parent',figure1,'XTick',[1 2 3 4 5 6],...
    'Position',[0.13 0.5939 0.3043 0.3311]);
% Uncomment the following line to preserve the X-limits of the axes
% xlim([1 6]);
grid('on');
hold('all');

% Create scatter
scatter(converters1,newlpc1,S1,C1,'Marker','*','Parent',axes1,...
    'DisplayName','lpc 0.25 vs converters');

% Create xlabel
xlabel('Number of redundant converters');

% Create ylabel
ylabel({'LPC of energy','(pounds/kWh)'});

% Create title
title('initial MTTF of 0.25');

% Create plot
plot(X1,Y1,'Parent',axes1,'LineWidth',2,'LineStyle','--',...
    'Color',[0 0.498 0],...
    'DisplayName','f(x) = (0.1724*x + 0.27) / (x + 0.3)');

% Create axes
axes2 = axes('Parent',figure1,'XTick',[1 2 3 4 5 6],...
    'Position',[0.5875 0.5939 0.3175 0.3311]);
% Uncomment the following line to preserve the X-limits of the axes
% xlim([1 6]);
grid('on');
hold('all');
```

```
% Create title
title('initial MTTF of 0.5');

% Create scatter
scatter(converters1,newlpc2,S1,C1,'Parent',axes2,...
    'DisplayName','lpc 0.5 vs converters');

% Create xlabel
xlabel('Number of redundant converters');

% Create ylabel
ylabel({'LPC of energy','(pounds/kWh)'});

% Create plot
plot(X1,Y2,'Parent',axes2,'LineWidth',2,'LineStyle','--','Color',[0 0 1],...
    'DisplayName','f(x) = (0.0578*x + 0.12) / (x + 1.478)');

% Create axes
axes3 = axes('Parent',figure1,'XTick',[1 2 3 4 5 6],...
    'Position',[0.13 0.11 0.3043 0.33]);
% Uncomment the following line to preserve the X-limits of the axes
% xlim([1 6]);
grid('on');
hold('all');

% Create title
title('initial MTTF of 0.75');

% Create scatter
scatter(converters1,newlpc3,S1,C1,'Marker','^','Parent',axes3,...
    'DisplayName','lpc 0.75 vs converters');

% Create xlabel
xlabel('Number of redundant converters');

% Create ylabel
ylabel({'LPC of energy','(pounds/kWh)'});

% Create plot
plot(X1,Y3,'Parent',axes3,'LineWidth',2,'LineStyle','--','Color',[1 0 0],...
    'DisplayName','f(x) = (0.041*x + 0.0877) / (x + 1.646)');

% Create axes
axes4 = axes('Parent',figure1,'XTick',[1 2 3 4 5 6],...
    'Position',[0.5875 0.11 0.3175 0.33]);
% Uncomment the following line to preserve the X-limits of the axes
% xlim([1 6]);
grid('on');
hold('all');

% Create title
title('initial MTTF of 1');

% Create scatter
scatter(converters1,newlpc4,S1,C1,'Marker','v','Parent',axes4,...
    'DisplayName','lpc 1 vs converters');
```

```
% Create xlabel
xlabel('Number of redundant converters');

% Create ylabel
ylabel({'LPC of energy','(pounds/kWh)'});

% Create plot
plot(X1,Y4,'Parent',axes4,'LineWidth',2,'LineStyle','--',...
    'Color',[0.749 0 0.749],...
    'DisplayName','f(x) = (0.035*x + 0.074) / (x + 1.775)');

% Create legend
legend1 = legend(axes1,'show');
set(legend1,'Position',[0.1933 0.8658 0.2292 0.05117],'FontSize',12);

% Create legend
legend2 = legend(axes2,'show');
set(legend2,'FontSize',12);

% Create legend
legend3 = legend(axes3,'show');
set(legend3,'Position',[0.2202 0.3928 0.2501 0.05117],'FontSize',12);

% Create legend
legend4 = legend(axes4,'show');
set(legend4,'FontSize',12);
```

L.1.10 Results curve fitting Program

```
function fiting(converters,lpc025)
%FITING    Create plot of datasets and fits
%   FITING(CONVERTERS,LPC025)
%   Creates a plot, similar to the plot in the main curve fitting
%   window, using the data that you provide as input.  You can
%   apply this function to the same data you used with cftool
%   or with different data.  You may want to edit the function to
%   customize the code and this help message.
%
%   Number of datasets:  1
%   Number of fits:  1


% Data from dataset "lpc025 vs. converters":
%    X = converters:
%    Y = lpc025:
%    Unweighted
%
% This function was automatically generated on 16-Feb-2010 17:04:54

% Set up figure to receive datasets and fits
f_ = clf;
figure(f_);
set(f_,'Units','Pixels','Position',[441 219 680 532]);
legh_ = []; legt_ = {};   % handles and text for legend
xlim_ = [Inf -Inf];       % limits of x axis
ax_ = axes;
set(ax_,'Units','normalized','OuterPosition',[0 0 1 1]);
set(ax_,'Box','on');
axes(ax_); hold on;


% --- Plot data originally in dataset "lpc025 vs. converters"
converters = converters(:);
lpc025 = lpc025(:);
h_ = line(converters,lpc025,'Parent',ax_,'Color',[0.333333 0 0.666667],...
     'LineStyle','none', 'LineWidth',1,...
     'Marker','.', 'MarkerSize',12);
xlim_(1) = min(xlim_(1),min(converters));
xlim_(2) = max(xlim_(2),max(converters));
legh_(end+1) = h_;
legt_{end+1} = 'lpc025 vs. converters';

% Nudge axis limits beyond data limits
if all(isfinite(xlim_))
   xlim_ = xlim_ + [-1 1] * 0.01 * diff(xlim_);
   set(ax_,'XLim',xlim_)
else
    set(ax_, 'XLim',[0.94999999999999996, 6.0499999999999998]);
end


% --- Create fit "fit 2"
ok_ = isfinite(converters) & isfinite(lpc025);
if ~all( ok_ )
    warning( 'GenerateMFile:IgnoringNansAndInfs', ...
```

```
        'Ignoring NaNs and Infs in data' );
end
st_ = [0.95716694824294557 0.48537564872284122 0.80028046888880011 ];
ft_ = fittype('rat11');

% Fit this model using new data
cf_ = fit(converters(ok_),lpc025(ok_),ft_,'Startpoint',st_);

% Or use coefficients from the original fit:
if 0
   cv_ = { 0.16960821363994999, 0.18274088832270571, 0.029132649852089 68};
   cf_ = cfit(ft_,cv_{:});
end

% Plot this fit
h_ = plot(cf_,'fit',0.95);
legend off;  % turn off legend from plot method call
set(h_(1),'Color',[1 0 0],...
     'LineStyle','-', 'LineWidth',2,...
     'Marker','none', 'MarkerSize',6);
legh_(end+1) = h_(1);
legt_{end+1} = 'fit 2';

% Done plotting data and fits.  Now finish up loose ends.
hold off;
leginfo_ = {'Orientation', 'vertical', 'Location', 'NorthEast'};
h_ = legend(ax_,legh_,legt_,leginfo_{:});  % create legend
set(h_,'Interpreter','none');
xlabel(ax_,'');               % remove x label
ylabel(ax_,'');               % remove y label
```

L.1.11 Reactive response CO2 emissions Program

```
%%                    RR v 1.5 (23.12.2009) (12:00)                       %%
% Reactive response maintenance strategy program for the calculation of
% CO2 emissions

%-----------------------------Inputs-------------------------------------%

Turbine_rating = 2; %Turbine power rating in MW
NT= 50;       % Number of turbines
NB=25;         % Number of boats
NH=25;         % Number of helicopters
D= 25;        % Distance from the coast in kilometer
BE= 120000;    % Boat Emissions of greenhouse gases in grams per kilometer
HE= 31200;    % Helicopter Emissions of greenhouse gases in grams per kilometer
K= 20;        % Number of years simulated
N= K*365;     % Number of days simulated
PW= 0.9;      % Probability to get a good weather
P= 1;      % Number of iterations of the main loop
TBPM= 365;  % Time Between Planned Maintenance Repairs in days
Capacity= 0.342; % Capacity Factor of wind turbine
Omega = P;  % Countdown to know how many main loops remain
Lamda = 2;  % Mean failure rate of the turbine

%--------------------Parameters of the Wind Turbines---------------------%

% Input of Automated component MTTF calculation from Lamda

aMTTF1 = (1 / (Lamda * 0.03)) * 24 * 365;      % Structure
aMTTF2 = (1 / (Lamda * 0.08)) * 24 * 365;      % Mean Time To Failure of the Yaw System
aMTTF3 = (1 / (Lamda * 0.03)) * 24 * 365;      % Mean Time To Failure of the Gears
aMTTF4 = (1 / (Lamda * 0.10)) * 24 * 365;      % Mean Time To Failure of the Sensors
aMTTF5 = (1 / (Lamda * 0.02)) * 24 * 365;      % Mean Time To Failure of the Drive
Train
aMTTF6 = (1 / (Lamda * 0.19)) * 24 * 365;      % Mean Time To Failure of the Control
System
aMTTF7 = (1 / (Lamda * 0.23)) * 24 * 365;      % Mean Time To Failure of the Electric
System
aMTTF8 = (1 / (Lamda * 0.03)) * 24 * 365;      % Mean Time To Failure of the Generator
aMTTF9 = (1 / (Lamda * 0.08)) * 24 * 365;      % Mean Time To Failure of the
Blades/Pitch
aMTTF10 = (1 / (Lamda * 0.10)) * 24 * 365;     % Mean Time To Failure of the Hydraulics
aMTTF11 = (1 / (Lamda * 0.05)) * 24 * 365;     % Mean Time To Failure of the Rotor Hub
aMTTF12 = (1 / (Lamda * 0.06)) * 24 * 365;     % Mean Time To Failure of the Mechanical
Brakes


MTTF1=round(aMTTF1/24);    % Mean Time To Failure of the Structure
MTTF2=round(aMTTF2/24);       % Mean Time To Failure of the Yaw System
MTTF3=round(aMTTF3/24);       % Mean Time To Failure of the Gears
MTTF4=round(aMTTF4/24);       % Mean Time To Failure of the Sensors
MTTF5=round(aMTTF5/24);       % Mean Time To Failure of the Drive Train
MTTF6=round(aMTTF6/24);       % Mean Time To Failure of the Control System
MTTF7=round(aMTTF7/24);       % Mean Time To Failure of the Electric System
MTTF8=round(aMTTF8/24);       % Mean Time To Failure of the Generator
MTTF9=round(aMTTF9/24);       % Mean Time To Failure of the Blades/Pitch
MTTF10=round(aMTTF10/24);      % Mean Time To Failure of the Hydraulics
```

```
MTTF11=round(aMTTF11/24);     % Mean Time To Failure of the Rotor Hub
MTTF12=round(aMTTF12/24);     % Mean Time To Failure of the Mechanical Brakes

MTTF = [MTTF1 MTTF2 MTTF3 MTTF4 MTTF5 MTTF6 MTTF7 MTTF8 MTTF9 MTTF10 MTTF11 MTTF12]; %↙
Vector of storage of the MTTF of all the components

MTTR1=round(95/24);  % Mean Time To Repair of the Structure
MTTR2=round(60/24);  % Mean Time To Repair of the Yaw System
MTTR3=round(145/24);  % Mean Time To Repair of the Gears
MTTR4=round(38/24);  % Mean Time To Repair of the Sensors
MTTR5=round(138/24);  % Mean Time To Repair of the Drive Train
MTTR6=round(45/24);  % Mean Time To Repair of the Control System
MTTR7=round(37/24);  % Mean Time To Repair of the Electric System
MTTR8=round(161/24);  % Mean Time To Repair of the Generator
MTTR9=round(89/24);  % Mean Time To Repair of the Blades/Pitch
MTTR10=round(32/24); % Mean Time To Repair of the Hydraulics
MTTR11=round(86/24); % Mean Time To Repair of the Rotor Hub
MTTR12=round(63/24); % Mean Time To Repair of the Mechanical Breaks

MTTR = [MTTR1 MTTR2 MTTR3 MTTR4 MTTR5 MTTR6 MTTR7 MTTR8 MTTR9 MTTR10 MTTR11 MTTR12]; %↙
Vector of storage of the MTTR of all the components


%-----------------Calculation variables initialisations-------------------%

A = zeros(1,P); % Vector of storage of the Time of unavailability for every main loops
NOF = zeros(12,1); % Vector of storage of the number of each kind of failure over all↙
the main loops
NOJOB= zeros(1,P); % Vector of storage of the Number Of Journeys Of the Boats for every↙
main loops
NOJOH= zeros(1,P); % Vector of storage of the Number Of Journeys Of the Helicopters for↙
every main loops

%---------------------Initiation of simulations---------------------------%

for u = 1 : P,↙
% Start of the main loop (Monte Carlo Iteration)


    NBA=NB;↙
% Number of boats available
    NHA=2*NH;↙
% Number of helicopters available

    W = binornd(1,PW,1,N);↙
% Random Vector representing the climate

    for i = 1 : N : NT*N,↙
% Generation of the matrix C representing the state of all the components of the wind↙
farm over the time

        C(1:12,i:(i+N-1))=[binornd(1,1/MTTF1,1,N);↙
% Each wind turbine is represented by 12 components (lines) with a rate of failure↙
defined above (ramdom vectors) over a the time (N days), and there are NT turbines
                           binornd(1,1/MTTF2,1,N);
                           binornd(1,1/MTTF3,1,N);
```

```
                              binornd(1,1/MTTF4,1,N);
                              binornd(1,1/MTTF5,1,N);
                              binornd(1,1/MTTF6,1,N);
                              binornd(1,1/MTTF7,1,N);
                              binornd(1,1/MTTF8,1,N);
                              binornd(1,1/MTTF9,1,N);
                              binornd(1,1/MTTF10,1,N);
                              binornd(1,1/MTTF11,1,N);
                              binornd(1,1/MTTF12,1,N)];

    end

    C(13,:) = zeros(1,NT*N);↙
% State Vector of the wind turbines

    C(14,:) = zeros(1,NT*N);↙
% Vector indicating when the wind turbine has to be subjected to a a planned↙
maintenance

    for j = TBPM : N : TBPM + N*(NT-1),↙
% Insertion of the first planned maintenance after TBPM days

        C(14,j) = 1;

    end


    TSPM   = zeros(1,NT);↙
% Time at which Starts the Planned Maintenance
    RTPM   = 12*ones(1*NT);↙
% Remaining Time of the Planned Maintenance
    TOFOWT = zeros(1,NT);↙
% Time at which the Failure of the wind turbine appear
    TORTOT = zeros(1,NT);↙
% Time Of Repair Of the Turbines

    for t = 1 : N,↙
% Start of the loop over the time (t being the time index in days)

        for i = 1 : NT,↙
% Start of the loop over the wind turbines of the wind farm

            if C(14,t+(i-1)*N) > 0,↙
% If the turbine requires a planned maintenance

                C(14,t+(i-1)*N:i*N) = ones(1,length(C(14,t+(i-1)*N:i*N)));↙
% The planned maintenance is required until it has been done (it means the wind↙
turbines goes and stays in the state 1)

                if (sum(C(1:12,t+(i-1)*N)) == 0 ) & (C(13,t+(i-1)*N) == 0) & (NHA > 0),↙
% If the turbine has no failed component, is not already in a maintenance process and↙
if an helicopter is available then the planned maintenance starts

                    TSPM(i) = t;↙
% Storage of the time at which starts the planned maintenance
                    C(13,t+(i-1)*N : i*N) = 5*ones(1,length(C(13,t+(i-1)*N : i*N)));↙
```

```
% The wind turbine goes to the state 5
                    NHA = NHA - 1;↙
% One helicopter is no more available

                end

            end

            if (sum(C(1:12,t+(i-1)*N)) > 0 ) & (C(13,t+(i-1)*N) == 0),↙
% If the wind turbine has at least one failed component and is not already in a↙
maintenance process

                TOFOWT(i)= t;↙
% Storage of the time at which the failure appears
                TOROT(i) = sum(MTTR'.*C(1:12,t+(i-1)*N));↙
% Calculation of the repair time required
                NOF = NOF + C(1:12,t+(i-1)*N);↙
% Addition of the failure(s) to the Vector of storage of the number of each kind of↙
failure over all the main loops

                if (C(1,t+(i-1)*N)+C(3,t+(i-1)*N)+C(5,t+(i-1)*N)+C(7,t+(i-1)*N)+C(8,t+↙
(i-1)*N)+C(9,t+(i-1)*N)+C(11,t+(i-1)*N)) > 0,

                    if (NBA > 0) & (W(t) == 0),↙
% If there is a boat available and the weather allows to start the repair, then the↙
repair starts

                        NBA = NBA - 1;↙
% One boat is no more available
                        C(13,t+(i-1)*N : i*N) = 3*ones(1,length(C(13,t+(i-1)*N :↙
i*N)));           % The turbine goes to the state 3

                    else↙
% Either the weather does not allow the repair or no boat is free, then the repair has↙
to wait

                        C(13,t+(i-1)*N : i*N) = ones(1,length(C(13,t+(i-1)*N : i*N)));↙
% The turbine goes to the state 1

                    end

                else↙
% If the failure(s) requires an helicopter

                    if (NHA > 0),↙
% If an helicopter is available, then the repair starts

                        NHA = NHA - 1;↙
% One helicopter is no more available
                        C(13,t+(i-1)*N : i*N) = 4*ones(1,length(C(13,t+(i-1)*N :↙
i*N)));           % The turbine goes to the state 4

                    else↙
% If no helicopter is available, then the repair has to wait

                        C(13,t+(i-1)*N : i*N) = 2*ones(1,length(C(13,t+(i-1)*N :↙
```

```
i*N)));            % The turbine goes to the state 2

                    end

                 end

             end

             if C(13,t+(i-1)*N) == 1,↙
% If the turbine is in the state 1 (Waiting for a boat)

                 A(u)=A(u)+1;↙
% One wind turbine is unavailable one day more

                 if (NBA > 0) & (W(t) == 0),↙
% If there is a boat available and the weather allows to start the repair, then the↙
repair starts

                     NBA = NBA - 1;↙
% One boat is no more available
                     C(13,t+(i-1)*N : i*N) = 3*ones(1,length(C(13,t+(i-1)*N : i*N)));↙
% The turbine goes to the state 3
                     A(u)=A(u) - 1;↙
% Decrease of one day, because it will be increased in the "if" about the sate 3

                 end

             end

             if C(13,t+(i-1)*N) == 2,↙
% If the turbine is in the state 2 (Waiting for an helicopter)

                 A(u)=A(u)+1;↙
% One wind turbine is unavailable one day more

                 if (NHA > 0),↙
% If an helicopter is available, then the repair starts

                     NHA = NHA - 1;↙
% One helicopter is no more available
                     C(13,t+(i-1)*N : i*N) = 4*ones(1,length(C(13,t+(i-1)*N : i*N)));↙
% The turbine goes to the state 3
                     A(u)=A(u) - 1;↙
% Decrease of one day, because it will be increased in the "if" about the sate 4

                 end

             end

             if (C(13,t+(i-1)*N) == 3) & (W(t) == 0),↙
% If the turbine is in the state 3 (in repair with a boat) and the weather allows the↙
repair, then the repairs continues

                 TOROT(i) = TOROT(i) - 1;↙
% The number of days to achieve the repair decreases of one day
                 A(u)=A(u)+1;↙
```

```
% One wind turbine is unavailable one day more
                NOJOB(u) = NOJOB(u) + 1;
% The Number Of Journeys Of the Boats increases of one

                if TOROT(i) == 0,
% If the repair is finished

                    NBA = NBA +1;
% One boat gets back available
                    NEW1 = length(C(13,t+(i-1)*N : i*N));
% Index giving the number of days to simulate from the end of the repair to the end of
the simulation
                    C(13,t+(i-1)*N : i*N) = zeros(1,NEW1);
% The turbine goes to the state 0 (working normally)

                    for j = 1 : 12
% Loop over the components of the repaired turbine

                        if C(j,TOFOWT(i)) == 1;
% If the component was one of the components which failed at the begining of the repair

                            C(j,t+(i-1)*N : i*N) = [binornd(1,1/MTTF(j),1,NEW1)];
% The component has been repaired and so has to be simulated by a new random vector
following the MTTF corresponding to the component

                        else
% If the component was one of the components which failed at the begining of the repair

                            C(j,t+(i-1)*N : i*N) = C(j,TOFOWT(i) : TOFOWT(i) + N - t);
% The component keeps the same random vector that it has at the moment of the begining
of the repair

                        end

                    end

                end

            end

            if (C(13,t+(i-1)*N) == 3) & (W(t) == 1),
% If the turbine is in the state 3 (in repair with a boat) and the weather does not
allow the repair

                A(u)=A(u)+1;
% One wind turbine is unavailable one day more

            end

            if C(13,t+(i-1)*N) == 4,
% If the turbine is in the state 4 (in repair with an helicopter), then the repair
continues

                TOROT(i) = TOROT(i) - 1;
% The number of days to achieve the repair decreases of one day
                A(u)=A(u)+1;
```

```
% One wind turbine is unavailable one day more
                NOJOH(u) = NOJOH(u) + 1;↙
% The Daily Number Of Journeys Of the Helicopters increases of one

                if TOROT(i) == 0,↙
% If the repair is finished

                    NHA = NHA +1;↙
% One helicopter gets back available
                    NEW2 = length(C(13,t+(i-1)*N : i*N));↙
% Index giving the number of days to simulate from the end of the repair to the end of↙
the simulation
                    C(13,t+(i-1)*N : i*N) = zeros(1,NEW2);↙
% The turbine goes to the state 0 (working normally)

                    for j = 1 : 12↙
% Loop over the components of the repaired turbine

                        if C(j,TOFOWT(i)) == 1;↙
% If the component was one of the components which failed at the begining of the repair

                            C(j,t+(i-1)*N : i*N) = [binornd(1,1/MTTF(j),1,NEW2)];↙
% The component has been repaired and so has to be simulated by a new random vector↙
following the MTTF corresponding to the component

                        else↙
% If the component was one of the components which failed at the begining of the repair

                            C(j,t+(i-1)*N : i*N) = C(j,TOFOWT(i) : TOFOWT(i) + N - t);↙
% The component keeps the same random vector that it has at the moment of the begining↙
of the repair

                        end

                    end

                end

            end

            if (C(13,t+(i-1)*N) == 5)↙
% If the wind turbine is the state 5 (In planned maintenance)

                NOJOH(u) = NOJOH(u) + 1;↙
% The Daily Number Of Journeys Of the Helicopters increases of one
                RTPM(i) = RTPM(i)-1;↙
% The Remaining Time of the Planned Maintenance decreases of one day
                A(u) = A(u) + 1;↙
% One wind turbine is unavailable one day more

                if RTPM(i) == 0,↙
% If the planned maintenance is finished

                    NHA = NHA + 1;↙
% One helicopter gets back available
                    RTPM(i) = 12;↙
```

```
% The Remaining Time of the Planned Maintenance of the turbine geys back to 12 days↙
(for the next planned maintenance)
                    NEW3 = length(C(14,t+(i-1)*N : i*N));↙
% Index giving the number of days to simulate from the end of the planned maintenance↙
to the end of the simulation
                    C(14,t+(i-1)*N : i*N) = zeros(1,NEW3);↙
% The vector indicating when the wind turbine has to be subjected to a a planned↙
maintenance gets back to 0
                    C(13,t+(i-1)*N : i*N) = zeros(1,NEW3);↙
% The turbine goes to the state 0 (working normally)

                    if (N-t) >= TBPM,↙
% If there is enough time to schedule another planned maintenance

                        C(14,t+TBPM) = 1;↙
% Scheduling of a new planned maintenance

                    end

                    for j = 1 : 12,↙
% Loop over the components of the repaired wind turbine

                        if (j == 1) | (j == 7) | (j == 9),↙
% If the component is not amongst the components repaired during the planned↙
maintenance

                            C(j,t+(i-1)*N : i*N) = C(j,TSPM(i) : TSPM(i) + N - t);↙
% The component keeps the same random vector that it has at the moment of the begining↙
of the planned maintenance

                        else↙
% If the component is amongst the component repaired during the planned maintenance

                            C(j,t+(i-1)*N : i*N) = [binornd(1,1/MTTF(j),1,NEW3)];↙
% The component has been "repaired" and so has to be simulated by a new random vector↙
following the MTTF corresponding to the component

                        end

                    end

                end

            end

        end

    end

  Omega = Omega -1↙
% The Countdown to know how many main loops remain decreases of one

end

NHJ = sum(NOJOH)/P;↙
% Number of Helicopter Journeys
```

```
TDRBH = 2*D*NHJ;↙
% Total Distance Run By the Helicopters
NBJ = sum(NOJOB)/P;↙
% Number of Helicopter Journeys
TDRBB = 2*D*NBJ;↙
% Total Distance Run By the Boats
ANOFPC = NOF/P;↙
% Average Number Of Failures Per Component
UOWF = sum(A)/P;↙
% Unavailabilty Of the Wind Farm (Sum of all the unavailability days over all the↙
turbines);
AOWF = (N*NT) - UOWF;↙
% Availabilty Of the Wind Farm (Sum of all the availability days over all the↙
turbines);
AOWFP = AOWF*100/(N*NT);↙
% Availabilty Of the Wind Farm in percent


%----------Calculation of the energy generated by the wind farm-----------%

Pw = Capacity * Turbine_rating * 10^6;     % Mean Power Generated by one Turbine in↙
Watt

EGBWF = (Pw * 24 * AOWF)*10^(-3);          % Energy Generated By the Wind Farm over the↙
K years in kWh

%--------Calculation of the quantities of greenhouse gases emitted--------%

QOGGH = TDRBH * HE;          % Quantity Of Greenhouse Gases emitted by the Helicopters↙
in grams
QOGGB = TDRBB * BE;          % Quantity Of Greenhouse Gases emitted by the Boats in↙
grams
TQOGG = QOGGH +QOGGB;        % Total Quantity Of Greenhouse Gases emitted

%----------------------DISPLAY OF THE RESULTS----------------------------%

InputTableName = ['Number of turbines                                         ';↙
% Table giving the names of the input data
                  'Capacity factor of the wind farm                           ';
                  'Turbine power rating                                       ';
                  'Number of boats                                            ';
                  'Number of helicopters                                      ';
                  'Distance from the coast in kilometer                       ';
                  'Boat Emissions of greenhouse gases in grams per kilometer  ';
                  'Helicopter Emissions of greenhouse gases in grams per kilometer ';
                  'Failure rate of wind turbines                              ';
                  'Number of years simulated                                  ';
                  'Probability to get a bad weather                           ';
                  'Number of iterations of the main loop                      ';
                  'Time Between Planned Maintenance Repairs in days           '];

InputTableNumber = [ NT Capacity Turbine_rating NB NH D BE HE Lamda K PW P TBPM]';↙
% Table giving the values of the input data

InputTable = [InputTableName, num2str(InputTableNumber)]↙
% Display of the input data
```

```
ResultTableName = ['Number of Helicopter Journeys
';                 % Table giving the names of the output data
                    'Total Distance Run By the Helicopters
';
                    'Number of Boat Journeys
';
                    'Total Distance Run By the Boats
';
                    'Availabilty Of the Wind Farm (Sum of all the availability days over
all the turbines)      ';
                    'Maximal Availability of the wind farm (Sum of all the simulated
days over all the turbines)';
                    'Availability of the wind farm in percent
';
                    'Energy Generated By the Wind Farm over the K years in kWh
';
                    'Quantity Of Greenhouse Gases emitted by the Helicopters in grams
';
                    'Quantity Of Greenhouse Gases emitted by the Boats in grams
';
                    'Total Quantity Of Greenhouse Gases emitted
'];


ResultTableNumber = [NHJ TDRBH NBJ TDRBB AOWF N*NT AOWFP EGBWF QOGGH QOGGB TQOGG]';
% Table giving the values of the input data

ResultTable = [ResultTableName , num2str(ResultTableNumber)]
% Display of the output data

%-------------------------Saving variables----------------------------------%
save('h:\alex.
mat','InputTableNumber','InputTableName','ResultTableNumber','ResultTableName')

%---------------------------------Shutdown----------------------------------%
   shutdown    %Shutdown the computer after the simulations
```